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Assessment of Responses to Climate Variation in the Marine Environment of Coastal Regions of the United States

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GLOBAL CHANGE RESEARCH PROGRAM

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Assessment of Responses to Climate Variation in the Marine Environment of Coastal Regions of the United States

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EXECUTIVE SUMMARY:

The scientific objectives of the U.S. Global Change Research Program (GCRP), coordinated by the Committee on Earth Sciences are to monitor, understand, and ultimately predict global change. A critical challenge in meeting these objectives will be to develop understanding of interactions among terrestrial, riverine, oceanic, and atmospheric systems that occur because of climate change. Research reported in this assessment of marine environmental change describes some effects of past climate variations on physical characteristics in United States coastal regions, and infers some of the changes that may occur due to global warming.

The motivation for an estuarine and coastal component of the EPA GCRP is that both sensitive ecological systems and highly populated areas are concentrated along coasts throughout the world, and many could be adversely effected if anticipated global warming occurs. Changes in physical and chemical parameters such as temperature, salinity, light, nutrient fluxes, sea level, and circulation have substantially effected coastal zone ecology. Physical conditions of coastal waters may provide some of the best opportunities for early detection of response to climate change. River runoff is an integrator of continental hydrologic processes and changes of runoff into coastal areas link coastal oceanic environment to changes in precipitation and land use. Coastal sea level change is caused by change in runoff, water temperature, and wind-forced circulation as well as land subsidence. Continued research will improve our understanding of coastal marine ecosystem responses. This research will permit interpretation of future environmental changes with respect to climate change.

Key research questions for the estuarine and coastal component of the EPA GCRP are:

(1) How has past and present climate variability influenced estuarine and coastal ecosystems?

(2) What physical, biological, and geochemical coastal zone processes and human activities interact with and may be effected by climate change?

(3) How accurately can predictions of future coastal impacts of global climate change be made?

These questions were discussed at workshop on "Coastal Ocean Physics and Climate Change: Approaches for the Assessment of Ecosystem Response" jointly sponsored by EPA, NOAA and the Texas Institute of Oceanography in January, 1990. A workshop proceedings document is in press. This workshop proceedings document briefly reviews:

- o Important physical features of U.S. continental shelves and estuaries,
- o Coastal physical processes effected by climate change,
- o Coastal ocean modeling methodologies,
- o Modeling scenarios of potential circulation and water mass changes,
- o Coastal ecosystems as analogues for climate change, and
- o Research task areas for modeling, observations and monitoring.

In this document, "Assessment of Responses to Climate Variation in the Marine Environment of Coastal Regions of the United States," assessments focus on regional spatial scale responses to potential <u>changes in large scale atmospheric and oceanic circulation</u>. Three coastal regions are selected from United States East, South and West coasts, to serve as examples of coastal responses to climate variation in differing coastal regimes. The **Mid-Atlantic Bight, the Northwest Gulf of Mexico**, and **Southern California** were selected for analysis because of exposure to oceanic and atmospheric circulation. This research seeks explanation of environmental effect of past climate variability in the selected regions and then, by analogy, relates predicted climate changes to changes in sea level, wind, and river runoff.

The order analysis follows a consideration of factors operating at a range of spacial scales, from global to local (Figure E-1, Page v). Section 1 of this report provides a brief review of important processes operating in different U.S. coastal regions that may be effected by climate change. Section 2 addresses a model based prediction of future climatic conditions based on doubled global atmospheric CO_2 concentrations. Section 3 describes regional changes in key parameters affecting specific coastal regions for periods of Northern Hemispheric warming and cooling. Section 4 compares model based predictions with regional scale changes based on historical data. Thus, this report considers the wide range of process scales depicted in Figure E-1.

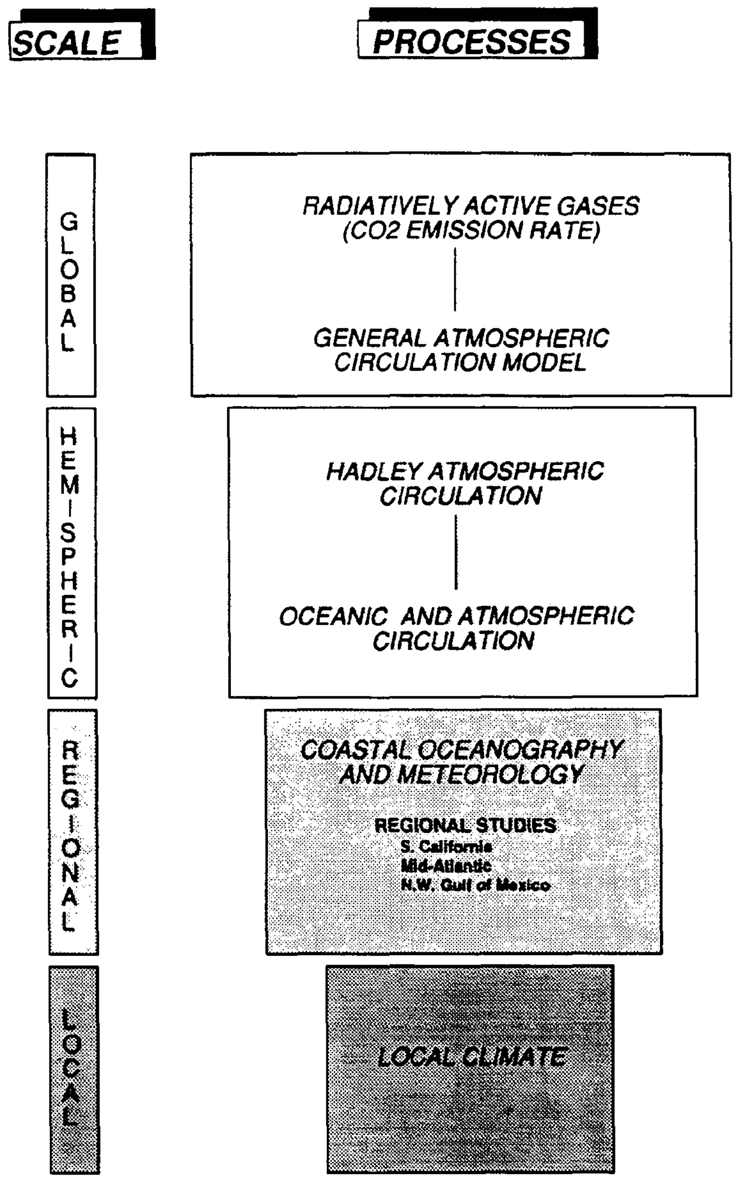

Figure E-1. Atmospheric and Oceanographic Process Scales

Large Scale Atmospheric Circulation

Wind generated stress on oceans from large scale wind regimes drive large-scale oceanic currents. Global climate change affects atmospheric circulation and wind-driven currents. Most coastal areas have different exposure to oceanic influences and wind than other areas. Therefore, environmental responses to effects of global-scale climate change will differ over United States coasts. Environmental changes may include change of any variable and changes could be opposite in different coastal areas depending on local effects.

A primary component of global atmospheric circulation is the Hadley Circulation. This circulation, driven by atmospheric heating at the equatorial surface, includes vertically rising air with surface easterly wind in equatorial regions and subsidence over the latitudes of the subtropical anticyclones (Figure E-2, Page vii). These Hadley Circulation subtropical anticyclones of the Pacific and Atlantic Oceans effect the meteorology of southern United States through wind-driven broad-scale ocean circulation and through coastal north/south winds which cause marine upwelling circulation. Two to three year interannual periods of change in Hadley Circulation have been observed and longer periods of change have been hypothesized from past research. Shorter periods of change in Hadley Circulation have been identified through cloud cover over oceanic areas monitored by satellite. Present research assesses past and future changes of the Hadley Circulation surface wind fields during periods of transition from "cold climatic regimes" and from "warm climatic regimes." The research relates circulation changes to changes in marine environments along U.S. coasts. Dramatic climate change effects have occurred at northern latititudes (Figure E-3), reflecting changes of the westerlie winds in mid-latitudes.

Modeling Large Scale Atmospheric Circulation Response to Doubled Atmospheric CO_2

The NOAA General Fluid Dynamics Laboratory (GFDL) Q-Flux Numerical General Climate Model (GCM) predictions in 1988 provided estimates of winds over continental United States and coastal areas for an atmosphere that contains the present concentration of carbon dioxide and for an atmosphere that contains double present carbon dioxide concentration. Winter (January mean) and Summer (August mean) wind fields, predicted for an atmosphere with the present concentration of carbon dioxide, are similar to wind fields of these months that were computed from the Comprehensive Ocean-Atmosphere Data Set (COADS). August wind fields predicted for a doubled carbon dioxide atmosphere, were also similar to the present wind climatology. January wind fields were different in an atmosphere with double carbon dioxide concentration, particularly in the area of the south and eastern coast; wind direction is predicted to veer (rotate in a clockwise direction) and turn southward in apparent association with a larger and westward extension of the Bermuda High (part of the Atlantic subtropical anticyclone). In effect, this change produced a winter wind that was more like the normal summer wind regime.

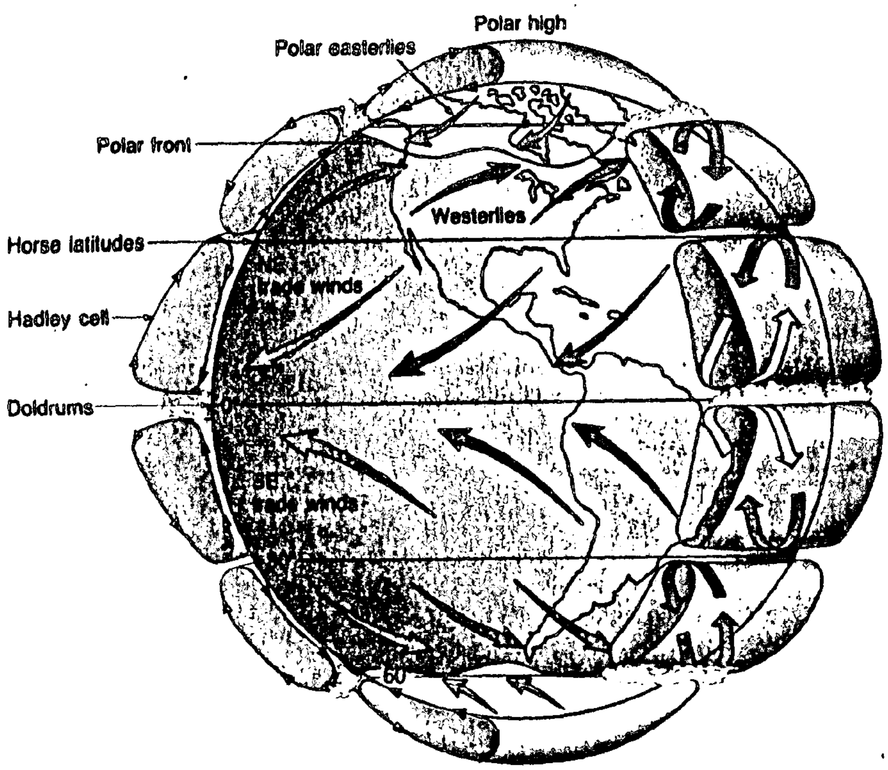

Figure E-2. A Schematic Representation of the Hadley Circulation(Lutgens, 1989)

Historical Analysis of Large Scale Atmospheric Circulation During U.S. Climatic Transitions

Area-weighted mean annual air temperature data from the United States and temperature analyses from northern hemisphere summarized temperature data, were used to select three periods from the historical COADS record. Two periods, 1889-1899 and 1970-1979 represent times when U.S. and northern hemisphere climate was warming and the period 1935-1944 represents time when change was from a warmer to a cooler climate. Based on COADS 2° area averaged data, wind anomaly was computed for Pacific and Atlantic oceans in the geographic area 130°E eastward to 10°W, 0° to 40°N. The anomalies show wind direction veers, turns southward, and speed increases along U.S. coasts when climate was becoming warmer. Wind direction backs (rotates in a counter-clockwise direction) with speed decreasing along U.S. coasts when climate was becoming cooler. Changes of regional wind speeds during the warming and cooling periods, westerly wind speeds, and hemispheric change of air temperature are illustrated in Figure E-4. Changes of winds during climate warming are similar to changes predicted for the earth atmosphere that has doubled carbon dioxide concentration and with a climate that becomes warmer. COADS surface pressure data were summarized for the same periods as for wind data. Subtropical anticyclones of the coastal Pacific region migrated toward the northwest during periods of transition toward warmer climate but are displaced southeastward during the period with climate cooling.

Potential Consequences in Selected U.S. Coastal Regions

Precipitation:

Increased southerly wind components in the southeast may increase moisture advection into continental U.S. and cause increased precipitation and land runoff. Runoff from the Potomac, Delaware, and Hudson River watersheds into the **Mid-Atlantic Bight** during the 1970's has been large and variable over 11 year periods but without large increase relative to earlier decades. Predicted East Coast precipitation by the GCM for the warmer climate is also increased. Records of river flow of the Arroyo Seco, representative of land runoff in **Southern California**, show the runoff tends to be decreased during periods of transition to warmer conditions. Increased river runoff in **Southern California** was observed during 1935-1944, a transition to colder climate. Flow records from the Mississippi show increases in the 1970's but multidecade trends are not well defined by records available for this study.

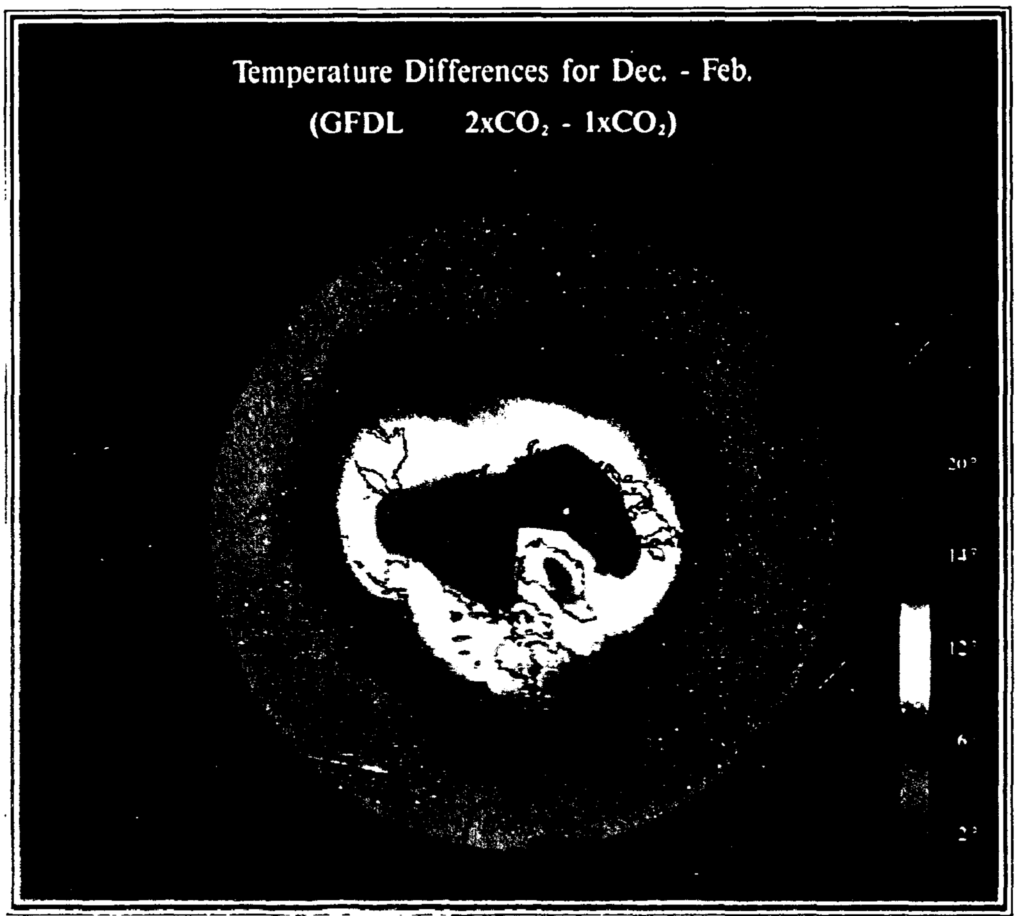

Figure E-3. Model-Estimated Northern Hemisphere Winter Air Temperature Change for Doubled Atmospheric Carbon Dioxide Concentration (Weatherald and Manabe, 1986).

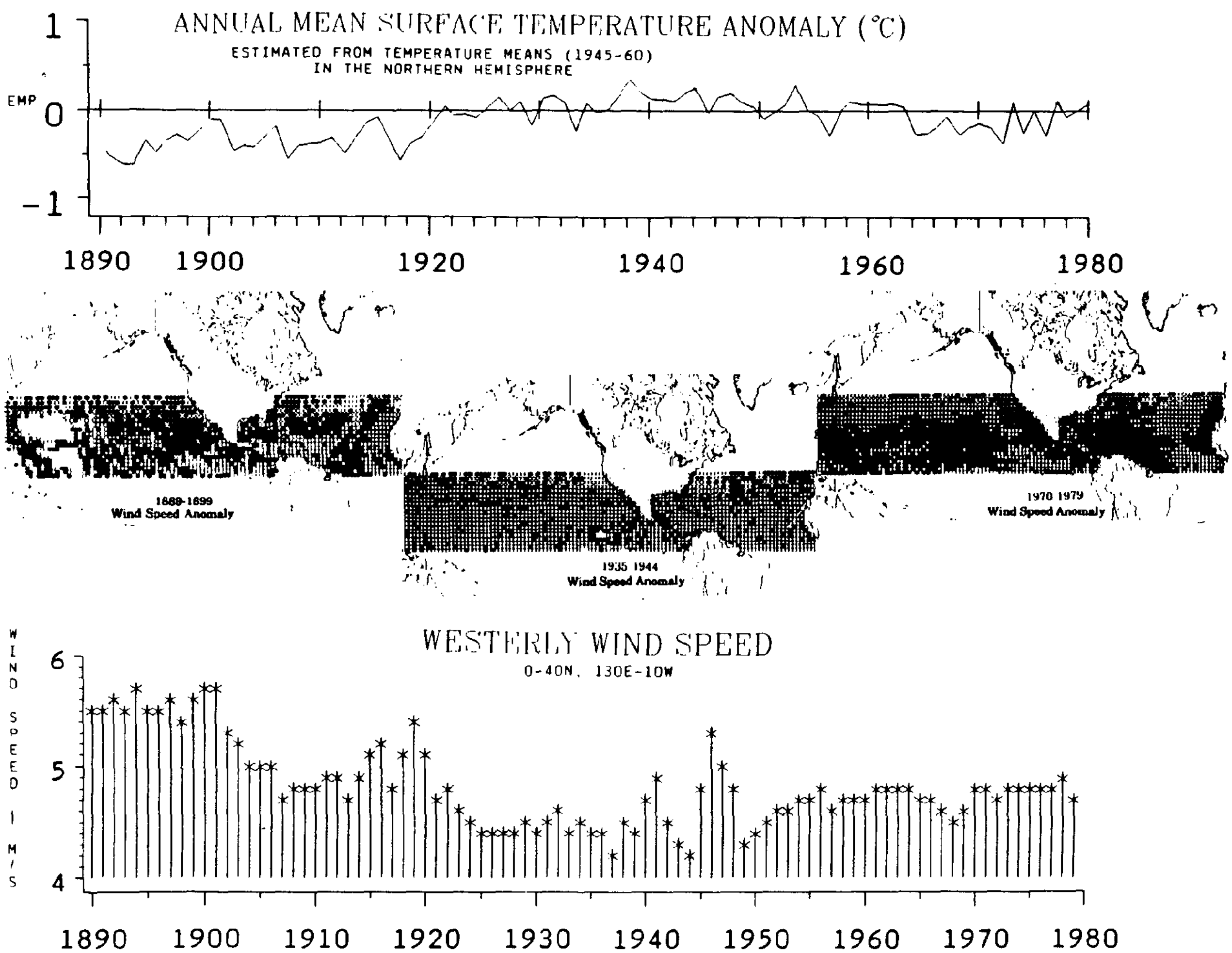

Figure E-4. **Changes in Northern Hemispheric Air Temperature, Regional Wind Regimes, and Westerly Wind Speeds.**

Wind-Driven Coastal Circulation:

During periods with warming climate, increased northerly wind increases wind-driven ocean circulation on the **Southern California** coast. Increased upwelling on the coast resulting from increased northerly wind causes lower coastal water temperature higher coastal salinity. Also, this will cause lowering of sea level.

Water-mass dynamics in **Mid-Atlantic Bight** promote southward drift that carries chemically enriched water southward along the New Jersey coast. Increased southerly wind components, which were found during periods of climate warming, produce wind stress to oppose near-shore drift. Increased upwelling resulting from wind stress along some coasts will bring oxygen rich "cold pool" water shoreward. Periods of upwelling that are extended into seasons of colder weather cause coastal water to be unseasonably warm and more saline.

Westward extension of the Bermuda High (part of the Atlantic area subtropical anticyclone) may promote the occurrence of late-spring northeasterly wind over the Mississippi delta area. Events of severe anoxic bottom water on the **Northwestern Gulf of Mexico** shelf have occurred because late spring northeasterlies caused an increase in the areas with highly stratified shelf water masses.

Sea Level Rise:

Steric effects are predicted to cause continued rise of sea level in the **Mid-Atlantic Bight**. With a warming climate the land runoff is expected to increase but most effects of sea level increase and runoff into this coastal area are expected in lacustrine estuaries. Future assessments of coastal environmental response to global climate change should include modeling studies of Chesapeake and Delaware Bay using predicted sea levels and runoff amounts.

Sea level increases in the Northwestern Gulf area during recent times are primarily associated with land subsidence and these changes are expected to continue.

GLOSSARY:

anticyclonic: Direction of motion which is clockwise in the northern hemisphere of earth.

anticyclone: A region on the earth surface in the northern hemisphere where wind motion is clockwise and atmospheric pressure on the earth surface is relatively high.

area weighted mean: A statistical parameter computed by summing the products of variables by the measure of the region of variable influence and then dividing the sum of products by the total sum of the region measures.

backing: Counter clockwise change in direction of wind relative to an observer where the wind direction of air movement is considered to be toward the observer.

California current: A southward flowing current near the west coast of the United States.

cyclonic: Direction of motion which is counter clockwise in the northern hemisphere of earth.

cyclone: A region on the earth surface in the northern hemisphere where wind motion is counter clockwise and atmospheric pressure on the earth surface is relatively low.

Davidson current: A northward flowing current near the west coast of the United States.

dynamic depth/height: A relative magnitude of a field or surface parameter that is associated with fluid motion.

Ekman transport: Net displacement of air or water from one location to another, relative to a fixed location on the earth, that is caused by acceleration from earth spin.

evapotranspiration: Change of water phase with plant extruded water going to a gas.

general circulation: Circulation in the atmosphere or oceans which has dimensions commonly associated with the size of earth hemispheres or ocean basins.

geopotential: A potential energy that is produced by the relative position of earth fluid mass. Surfaces with equal geopotential are designated geopotential surfaces.

geostrophic: A descriptive term that refers to air or water motion when, in the absence of significant friction forces, the forces of pressure are balanced by the Coriolis forces.

Hadley Circulation: Circulation of air in the troposphere of earth equatorial regions which is driven by atmospheric heating at the earth surface. In this Circulation, a net ascension of air from low latitudes is followed by latitudinal movement of air to higher latitudes, air subsidence at latitudes of the earth subtropical anticyclones, and surface wind which is caused by the resulting differences of air pressure between the anticyclones and equatorial low pressure where the heating occurs.

intertropical convergence zone: The earth equatorial zone where wind that is associated with the northern hemisphere meets wind that is associated with the southern hemisphere.

latitudinal: Motion across latitudes.

lacustrine: A water body characteristic in which the water area is semienclosed geographically from a larger water area which is commonly a sea or ocean.

long wave: Periodic variation in the atmosphere and oceans that is associated with influence regions with distances of thousands of kilometers.

orographic: Influenced by geographic features, usually mountains.

meridional: Motion along earth longitudes or a measure of extent that is associated with longitudes.

Milankovich cycles: Periodic changes in orientation of the earth in space relative to the sun with periods in the order of thousands of years.

palustrine: An adjective that refers to association with a marsh environment.

phenological: A term that references association with plants.

steric: Refers to conditions associated with pressure and density effects.

trough: A term that refers to a minimum of a field or surface.

upwelling: Oceanic circulation of water commonly caused by wind force which brings subsurface water toward the surface.

veering: A clockwise change in direction of wind relative to an observer where the wind is considered to move air toward the observer. This direction change is opposite to backing of wind.

Acknowledgement

Resources supporting research, which developed results presented in this report, were provided through the United States Environmental Protection Agency Global Change Research Program (GCRP).

This research developed from ideas presented at the "Coastal Ocean Physics and Climate Change" workshop in January, 1990. The workshop participants presented many ideas that were eventually used in the research conducted here at the EPA Environmental Research Laboratory, Narragansett (ERLN). Don Block and Cary Gentry, of the Atmospheric Research and Exposure Assessment Laboratory (AREAL) mapped data summaries for many of the figures included within this document. Document reviews were provided by George Mapp, Sharon LaDuc and Peter Finklestein at AREAL, and by Jan Prager, John Gentile and Wayne Munns at ERLN.

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PREFACE

Scientific objectives of the U.S. Global Change Research Program (GCRP), coordinated by the Committee on Earth Sciences are to monitor, understand, and ultimately predict global change. A great challenge in meeting these objectives will be to develop understanding of interactions among terrestrial, riverine, oceanic, and atmospheric systems that occur because of climate change.

Motivation for the estuarine and coastal component of the EPA GCRP is that both sensitive ecological systems and highly populated areas are concentrated along the coast throughout the world, and many could be adversely effected if anticipated sea level and climate changes occur. River runoff is an integrator of continental hydrologic processes that link coastal oceanic environment to changes in precipitation and land use. Coastal sea level change is caused by runoff, water temperature change, and wind forced circulation as well as land subsidence. Physical conditions of coastal waters are expected to respond quickly to climate change, and may be interpreted for early detection of climate change. Changes in key physical and chemical parameters such as temperature, salinity, light, nutrient fluxes, sea level, and circulation have effected coastal zone ecology in the past. Continued research will improve our understanding of coastal marine ecosystem responses and permit interpretation of ecological changes with respect to climatic changes.

Key research questions for the estuarine and coastal component of the EPA GCRP are:

(1) How has past and present climate variability effected estuarine and coastal ecosystems?

(2) What physical, biological, geochemical coastal zone processes, and human activities interact with and may be effected by climate change.

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Assessssment of Responses to Climate Variation in the Marine Environment of Coastal Regions of the United States

1. INTRODUCTION

Recent increases in the atmospheric concentration of a number of radiatively important trace gases (RITGs) are attributed to activities such as fossil fuel combustion, deforestation, cement manufacture, agricultural practices and production of chlorofluorocarbons (CFCs). These increases raise concerns about global warming because these gases absorb long wave length radiation. Atmospheric CO_2 concentrations may double by the middle of the next century. Regional climate changes, predicted through general climate models (GCMs) operating with double CO_2 atmosphere, are expected to cause significant changes in agricultural productivity. (Izrael and Hashimoto, 1990). These expectations are developed through use of productivity analogues based on historical productivity records. Analogues from historical records are used in this assessment of the marine environment to develop prediction of change in coastal regions.

During the Pleistocene (approximately the last 1.6 million years), atmospheric CO_2 fluctuations of 30-50% occurred with lows during glacial and highs during interglacial periods. Atmospheric CH_4, another RITG, was also low during glacials and high during interglacial periods. Thus, changes in atmospheric RITG concentration occur with climate change during glacial cycles. Ice core analysis from Antarctica (Barnola et al., 1987) provides a historical record of interpreted climate over a period of 160,000 years from the past with CO_2 concentration. Since CO_2 changes parallel climate change, the importance of CO_2 as a cause of climate change is not clearly defined (Siegenthaler, 1988).

Recently, atmospheric CO_2 concentrations have increased by about 0.4% per year. Since mid 1987 this rate has increased to about 0.7% per year. The rate of increase in atmospheric carbon sources is larger than the rate of change in the terrestrial and marine "sinks" for these gases. Atmospheric CO_2 increase is much greater than expected from fossil fuel combustion alone. The increased rate of change may be caused by deforestation and earth warming that led to decrease in the rate of oceanic uptake of CO_2. The measured rate of CO_2 increase and projected doubling of atmospheric CO_2 concentrations by the middle of the next century is unprecedented in the geological record during the quaternary.

Atmospheric temperature and radiation are parameters of climate and these variables cause change in all of the earth's environments. However, climate cannot be measured directly because it is the collective effect of all its parameters. This ensemble of effects has been in continuous change over time in a generally defined periodicity of tens of thousands of years (Flint, 1957). There are measurable changes, apart from seasonal change, over much shorter periods but the significance of change compared to a normal or expected climate condition is poorly defined. In the United States, meteorological variability may hinder development of a precise normal since record periods are commonly short relative to temporal scales of variability. However, climate change can be assessed with respect to reaction of selected variables in specific environments. This study describes coastal marine environmental response to the variables river-runoff, sea-level, and wind effects. Each near-shore coastal area and estuary of the United States is uniquely different from all others. Each area is expected to respond to climate change in unique ways. Initially, estimates of response for a few areas are assumed adequate to develop a sense for general trends of response to climate change and analogues of change. For initial analyses the regions of Southern California, North Western Gulf of Mexico, and Mid-Atlantic Bight are chosen. These are coastal areas influenced by large continental watersheds or exposure to geographically unique oceanic influences, and also areas where sufficient environmental data are available to identify present characteristics of environment.

Climate variation forcing during the Pleistocene period is identified with Milankovich orbital cycles of the earth (Kutzbach and Otto-Bliesner, 1982). Glacial-interglacial cycles are related to variations in earth orbital parameters (19K and 23K year variations in precession, 41K yr cycle in axial tilt, and 100K yr cycle in eccentricity). These orbital variations affect the spatial and temporal distribution of solar radiation reaching earth. Additional forces of future climate change are anticipated from changes of radiation balances within the earth's atmosphere caused by RITGs. Past atmospheric radiation balance changes may have amplified astronomical causes of climate change but in modern times radiation balance changes may be primary causes of change. Therefore, use of geographically-associated climate changes from the past demand judicious use as analogues or examples for the future. The analogues of world climate change from coastal areas of the United States in this paper are from model results and extrapolation of climate conditions over the past few hundred years. Changes of the past few hundred years, caused by Milankovich cycles, are assumed small. Temperature changes estimated in transition from interglacial to glacial periods were on the order of a thousandth of a degree per year. The yearly amount of change was much greater in transition back to interglacial periods. During the past few centuries, long period temperature changes are observed on the order of tenths of degree per year. In this report, Milankovick cycles are ignored, since the research focus is on comparison of climate conditions over the past few centuries and in prediction of climate change for the next century, rather than on time scales of thousands of years.

1.1 Climate Change in the United States

Climate change can occur as change in a single variable of the atmosphere or in many variables. These changes are decreases or increases depending upon association among variables. In addition, interdependence of variables may change with geographic area. Therefore, changes in radiation balances within the atmosphere could cause different change in meteorological and oceanic variables in different geographical areas. This could produce widely varying climate conditions and climate change in the United States could be different from other geographic areas.

Paleontologic analyses indicate that global air temperature differences between glacial and interglacial periods were on the order of 8° C (Flint, 1957). Changes in ocean circulation resulting in the closure of the Middle American Seaway (Hamilton, 1965; Keigwin, 1976) and an intensified late-Cenozoic orogenic phase (Hamilton, 1965) explain the relatively sudden onset of Northern Hemisphere ice-sheet formation. Atmospheric circulation during the pleistocene is similar to the circulation of modern times. Global-mean temperature's are similar to the present but fluctuate with periodic glacial changes. This caused repeated large-scale latitudinal displacements of climatic zones by as much as 20 to 30 degrees (Kennet, 1982). An enhanced low- latitude atmospheric circulation, the Hadley Circulation, during the Pleistocene (Nyberg, 1951) is attributed to large meridional temperature gradients caused by cool mid-latitudes. The global temperature fluctuations during glacial-interglacial cycles are considerably larger than variations of 1° C, deduced from measurements and phenological data over the past 600 years (Figures 1a.,1b., Page 4).

Evidence for change toward colder temperatures in central Europe (Pfister, 1988) during the 18th century (Figure 1a., Page 4) is augmented by evidence of glacial maximums in Alaska and in Central Europe (Flint, 1957) during the same period. This suggests some continuity of climate trends in Europe and North America but the 1/2° C difference between the 15th century and the 20th in central Europe may be different from the magnitude of change in North America. A record of temperature anomaly (Figure 1b., Page 4) from the northern hemisphere (Jones et al., 1982) appears to overlap the grape harvest data. The combined records provide a record of varying temperature from the 14th century in the northern hemisphere.

Phenological or sedimentary analyses of climate are not totally applicable for extension of single variable records backward in time because phenological and sedimentary conditions often are dependent on multiple variables. For example, a temperature variation record inferred from tree ring analyses (Fritts, 1980) provides estimates of relative spatial variation of temperature over the United States in the 17th century (Figure 2.). Tree ring variations are also caused by moisture

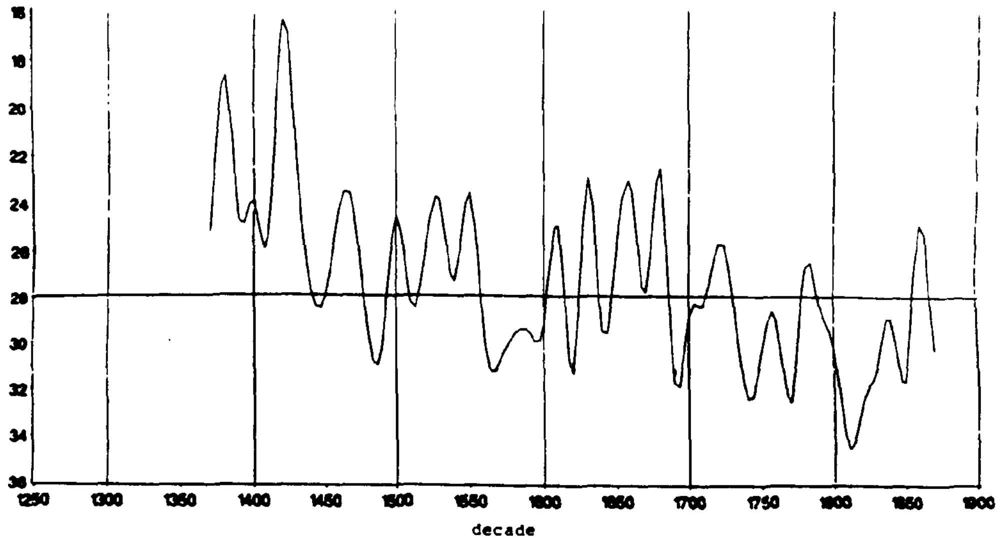

Figure 1a. The Decadal Mean of the Number of Days to Grape Harvest From September One in Central Europe: An Analog of Atmospheric Surface Temperature (illustration from Pfister, 1988).

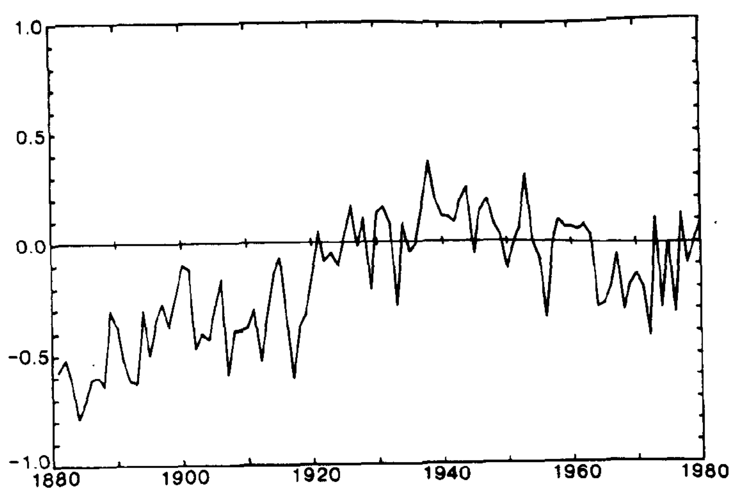

Figure 1b. Annual Mean Surface Temperature Anomaly (°C) Estimated from Temperature Means (1945-60) in the Northern Hemisphere (illustration from Jones, Wigley, and Kelly, 1982).

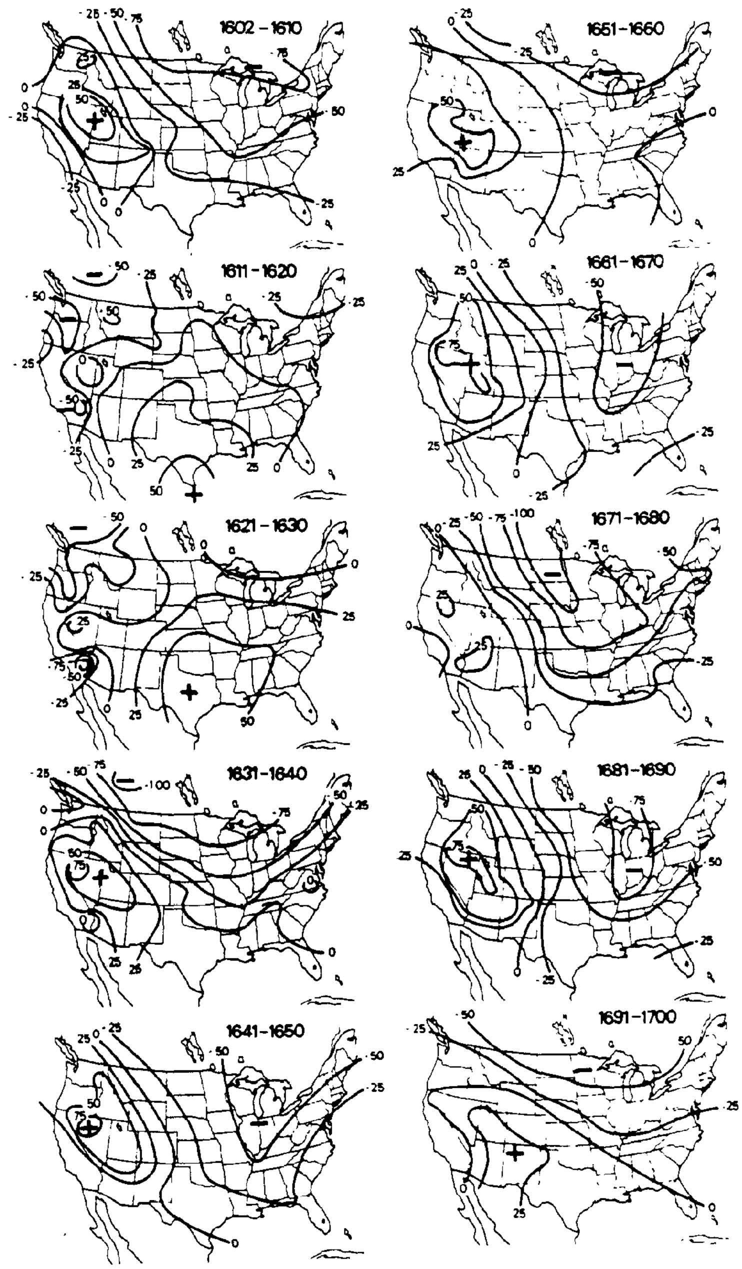

Figure 2. Estimated Mean Temperature Differences (°C) for Decades of the Seventeenth Century Based on Tree Ring Analysis (illustration by Fritts, 1980).

availability. Therefore, these inferred temperature distributions cannot be as precise as distributions deduced from modern measurements. However, these 17th century temperature distributions are supported by reports of the 1607-1608 and 1683-1684 winters that were particularly severe in New England and the northeastern United States (Forry, 1843). These winters occur in the periods shown on the figure by Fritts to be the periods of large temperature decreases from normal in the northeastern area.

Long and continuous records of environmental variables from the United States are of interest because they give the recent trend of change in the variables that produce climate. Unfortunately, the period of recorded environmental measurement in the United States is short with respect to periods usually associated with climate variation. Although the period of recorded measurements is longer for Europe, the possibility of different trends in climatic change in different areas clouds the interpretation for the United States. A few records of meteorological measurement with breaks are available in the United States from the mid-1700's but records with more continuity are available from the mid-1800's. Spatial coverage of observations to permit meteorological analysis begins in the late 1800's (Bigelow, 1909 and Figures 3a. and 3b., Pages 7 and 8). From the 19th century to the present, observation stations have moved, observation techniques changed, and observation station locations have been encroached by landscape changes and urbanization. These changes have caused differences in meteorological measurements that are similar to temporal changes associated with climate variation.

A temperature record for the United States (Figure 4., Page 9) is derived from average of air temperature measured by observation stations in the contiguous United States. The long-period temporal variation of temperature in the northern hemisphere is of larger magnitude in latitudes north of 64°N (Hansen and Lebedeff, 1987 and Figure 5, page 15). Relatively high Northern Hemispheric temperature during 1935-45 and temperature decline to about 1970 is similar to temperature anomaly changes in Figure 1b., Page 4. Temperature record variation in the United States is similar to variations over the Northern Hemisphere for much of the record except since about 1970. Change in any parameter of climate can cause change in other parameters. Because of regional differences in parameters of climate, short period temperature trend differences are not unexpected. Palutikof et al. (1984) compared temperatures and precipitation amounts during the periods 1901-20 and 1934-53. Temperatures during 1934-53 were about 0.5 - 1.0° C higher in the United States mid-west. Comparison of meteorology of the two periods is useful as a comparison of possible conditions under warmer climate. Precipitation increased by more than 0.5 standard deviations in coastal areas during the warmer period and decreased 0 - 0.5 standard deviations in central United States. However, trends of temperature and precipitation change are not statistically correlated (Hanson et al., 1989).

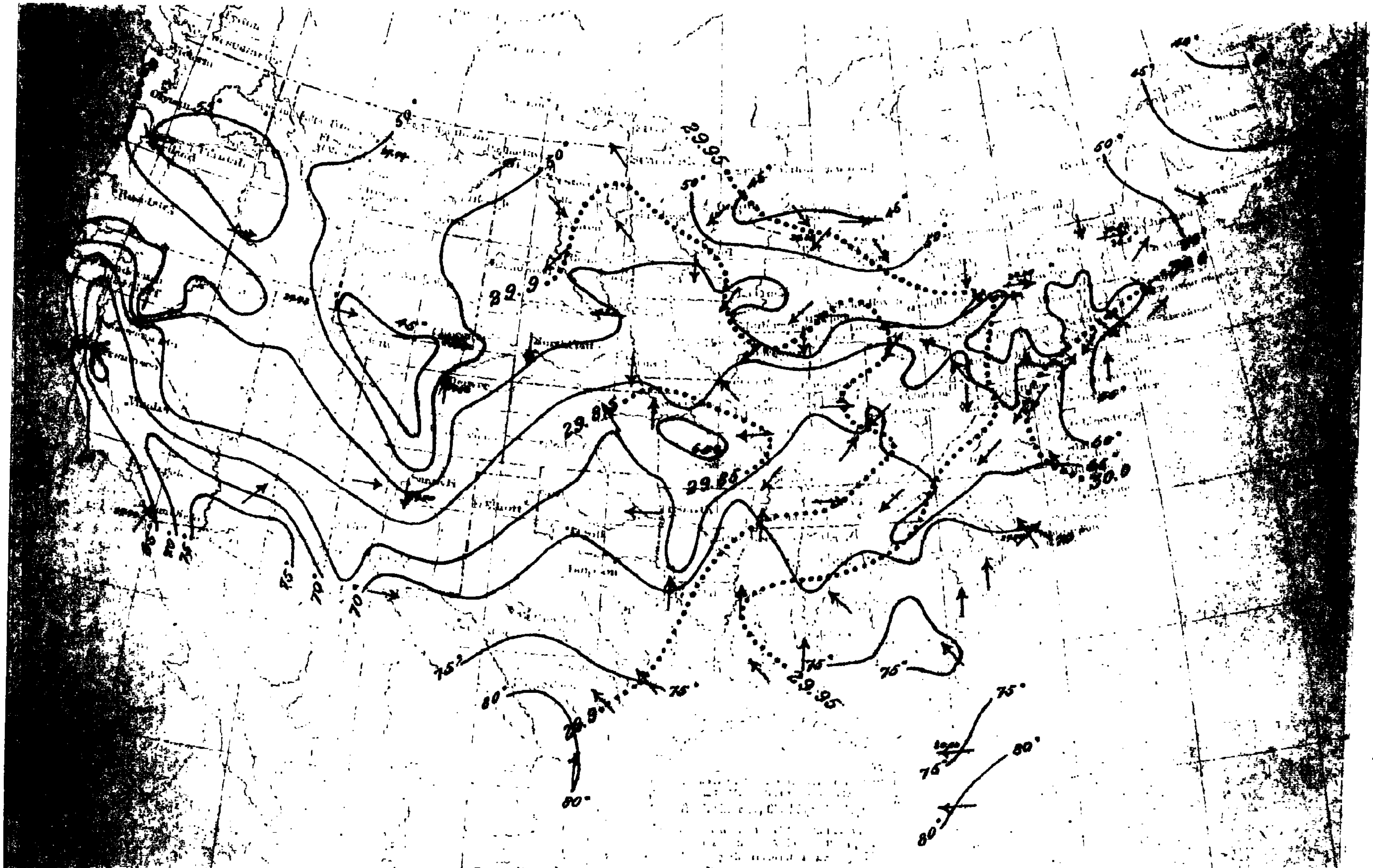

Figure 3a. Monthly Mean Isobars, Isotherms, and Wind for October 1873 (U.S. Signal Office, 1891).

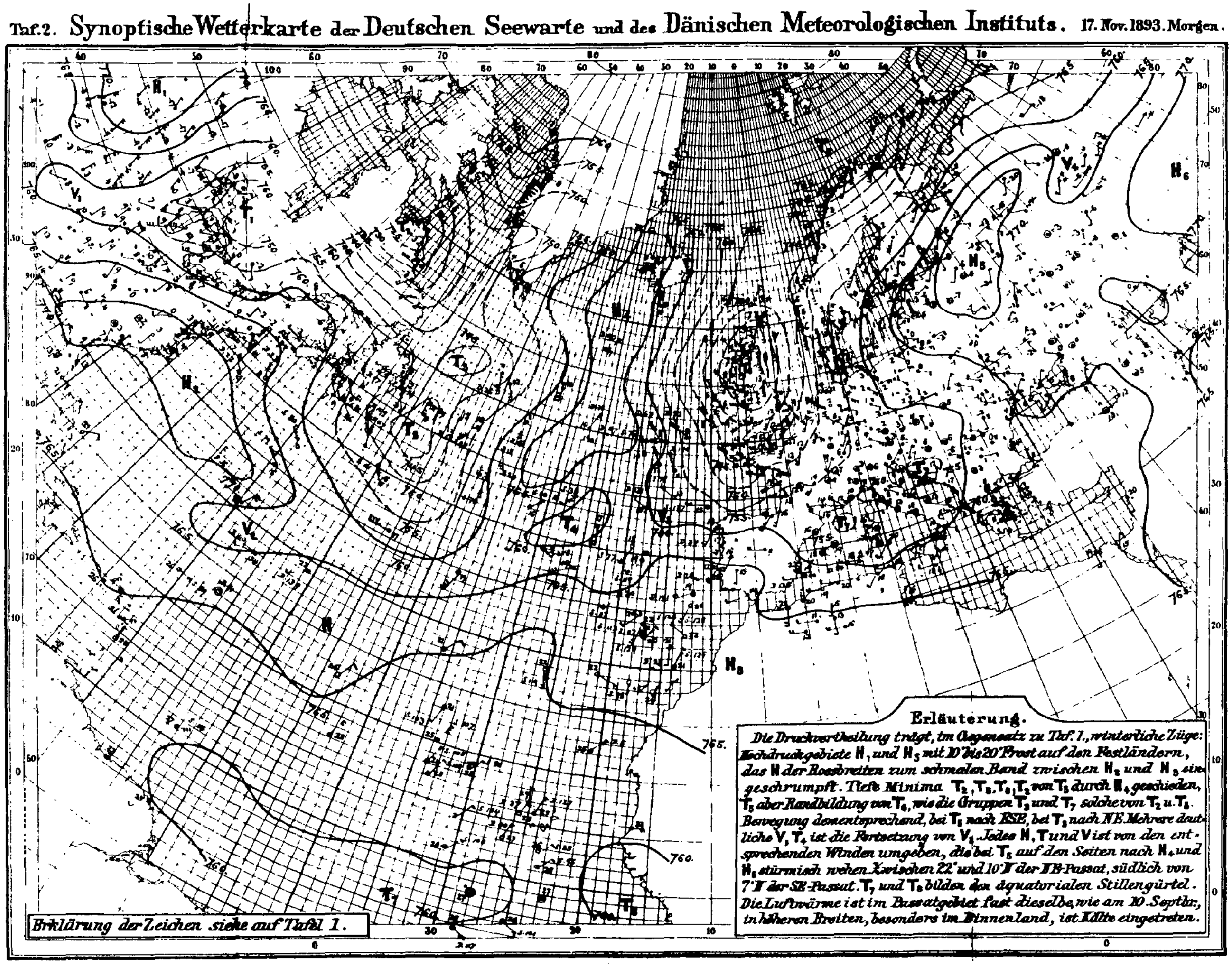

Figure 3b. Synoptic Meteorological Analysis for the Morning, September 10, 1893 (Koppen, 1899).

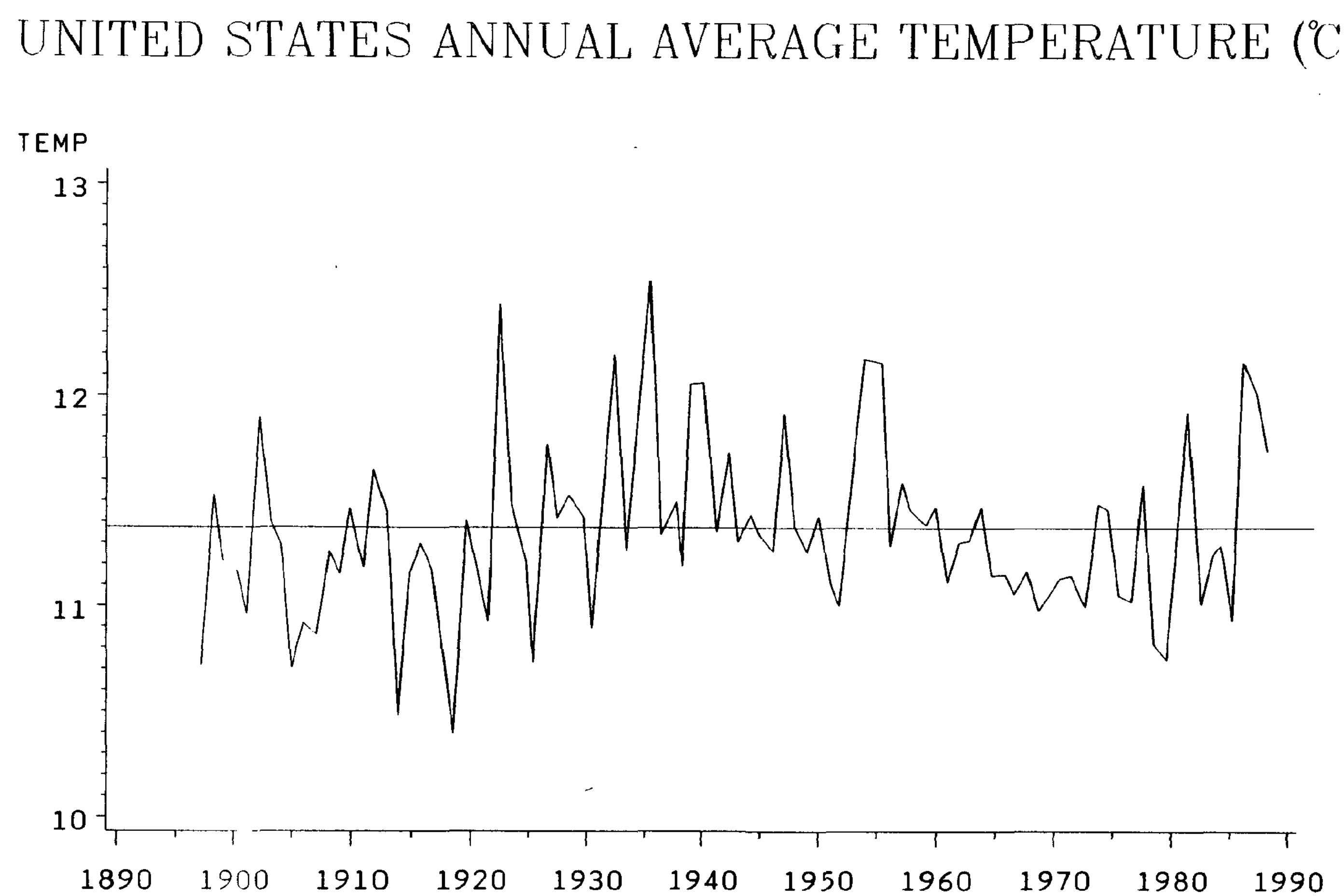

Figure 4. Annual Mean Temperature in the United States (M. La Brecque, 1989).

1.2 Atmospheric Circulation

In general, climate in the United States is controlled by global-scale circulation of the atmosphere but is influenced by coastal oceans linked to major oceanic current systems. Over the United States, this broad-scale atmospheric circulation includes a mid-continental trough of the westerly wind and subtropical anticyclones on the south east and south west coasts. Other broad-scale circulation features that are associated with change in the anticyclones and trough are the Aleutians-area low atmospheric pressure (the Aleutians Low), the North Pacific Subtropical Anticyclone, and the North Atlantic Subtropical Anticyclone (the Bermuda High). These circulation features of the mid-latitude westerly wind are influenced by broad-scale atmospheric circulation in equatorial regions. One of these circulation systems is the Hadley Circulation.

The Hadley Circulation is driven by atmospheric heating in equatorial regions that produces vertical air-mass advection in approximate proportion to the amount of heating. The vertical motion leads to meridional advection of air-mass to the latitudes of the subtropical anticyclones. The size of the anticyclones is correlated to the vertical air-mass advection. Changes of the Hadley Circulation in the Pacific and Atlantic areas are caused by wind-forced oceanic circulation (and the resulting water temperature changes) that is correlated to the size of the subtropical anticyclones (Godshall, 1990). The Circulation changes are also correlated to changes in the California Current and the Gulf Stream (Wallace and Gutzler, 1981). The eastern part of the Pacific subtropical anticyclone influences meteorological conditions in Southern California. The western part of the Atlantic subtropical anticyclone, the Bermuda High, influences conditions in southeastern United States.

Research seeks to identify conveniently monitored features of circulation that may be used as analogues of the ensemble of changes related to the circulation. Records of change in analogues may be useful indicators of climate change trends. Variation in the Hadley Circulation of the equatorial Pacific and Atlantic oceans has been related to multi-year variation of the subtropical anticyclones (Godshall, 1971). Therefore, this circulation may prove to be a useful analog of meteorological and oceanographic changes on southern coasts of the United States.

Between 1916-1955, there was intensification of the Bermuda High (Tollner, 1956), a pressure decrease between Iceland and Labrador, intensification of trade winds, and increased water temperatures in the Gulf Stream south of Newfoundland (Lamb and Johnson, 1959; Bjerknes, 1960). These changes of the Atlantic ocean and atmospheric circulation may have been related to change in the Hadley Circulation but there was no measurement of the Hadley Circulation to verify this. Water temperature anomaly from the 1900's through 1960's (Jones et al., 1982) showed the water temperature differences between equatorial and north Atlantic were larger during the period 1915 to 1940 than after 1940.

In the United States, location of the mid-continental trough of the westerly winds influences meteorological conditions over eastern parts of the country including the coastal regions. Significant change of meteorological conditions could result with a climate-related change in this trough as well as in the long-wave pattern of general atmospheric circulation. The trough is influenced by flow of westerlies over the Rocky Mountains. The mountains cause wind deceleration in the lower troposphere and a pattern of convergence and divergence of air-mass in the lee-waves of the mountain range. These wave patterns influence precipitation distribution in central United States (Reiter, 1961). Seasonal variations in atmospheric heating in the northern Hemisphere do not produce significant shifts in the mean position of the long-wave patterns (Bolin, 1950) and the orographic effects seem to be most influential for trough position. Therefore, a tentative deduction is that climate change from atmospheric warming will not cause shift in the position of the mid-continental trough.

1.3 Physical Properties of the Marine Environment

Physical properties of selected marine coastal regions are reviewed here to provide background for description of changes in some of the variables. Any area of United States coast may have different environmental response to global-scale climate change than another area because of different exposure to ocean circulation effects etc. Three coastal areas are analyzed here to provide a representative assessment of possible responses. Within any of the areas many characteristics of the environment may change but these analyses will address environmental response to wind, river runoff, and sea level changes that are caused by climate change.

The Mid-Atlantic region, roughly defined as the coastal region seaward to the shelf break from Cape Hatteras to Long Island, is selected for analysis because of large estuarine environments that are sensitive to variation in precipitation in northeastern United States and to oceanic circulation features of the shelf. The Northwest Gulf of Mexico is selected for climate impact analysis because of the influences of river runoff variations on water quality and the control of shelf circulation by wind-stress. A major source process for the nutrient chemicals input to the Gulf of Mexico ecosystems is the seaward flux of chemicals that results from flooded coastal margins. The processes associated with flooding may be altered by sea-level rises commonly associated with global climate change. The Southern California coast is selected for analysis because it is an area of coastal-water circulation forced by winds that are part of the broad-scale atmospheric processes in Hadley Circulation.

1.3.1 Mid-Atlantic Bight

The lacustrine estuaries of the area, Chesapeake Bay and Delaware Bay, have physical characteristics that are expected to respond to climate change effects differently from the responses of the open coast that are analyzed here. The special consequences of climate change on these water bodies will not be presented in this report.

Mid-Atlantic Circulation

The prevailing current on the open shelf is southward at all depths (Bumpus, 1973) but the near-shore waters, within the 90m isobath, have spatially and temporally varying circulation that changes with wind forcing, tidal influences, and stratification. In deep waters where the prevailing current is southward in all seasons and not influenced by seasonal wind changes, the circulation is a geostrophic balanced flow where the denser water is seaward. This southward current is assimilated into the western margin of the Gulf Stream over the area between Chesapeake Bay and Cape Hatteras.

A component of the southward drift is a cold water coastal-drift that moves southward from the Gulf of Maine (Godshall et al., 1980). A subsurface part of this drift (identified as Gulf of Maine intermediate water) contributes to the cold pool water on the southern flank of Georges Bank, and this water is found in a bottom layer current of the mid-shelf (Hopkins and Garfield, 1977). Production of the cold pool water-mass is dependent on severity of winter weather; the greater the wind-forced mixing and surface cooling, the larger the pool.

Because of out-flow of fresh water from the Hudson River, there is a weak southward drift of Bight water along the coast of New Jersey. The drift is commonly obscured by local wind forced circulation (Nuzzi, 1973). The chemical-nutrient and waste loadings to Bight waters contributes to lowered concentrations of dissolved oxygen in the Bight and in coastal waters of New Jersey (Swanson and Sindermann (eds), 1979, Segar and Berberian, 1976; Stoddard, 1989). The southward drift may continue along the coasts of Delaware and Virginia (Williams and Godshall, 1977) under conditions of maximum stratification in late summer. At this time of year, winds are relatively weak and the stratification reduces wind forced acceleration of the bulk of coastal water mass.

Summer season winds are typically southwesterly and, at depths less than 50m, the near-shore drift is northerly with upwelling in the area off Chesapeake Bay and coast of New Jersey (Norcross and Austin, 1988). This causes the cold pool waters to move shoreward and maximum bottom water temperatures are delayed until fall (Hicks and Miller, 1980) when wind becomes northerly and upwelling ceases. Autumnal cooling of coastal surface waters causes overturning and isothermal conditions (Houghton et al., 1982), general obscuration of the cold pool, and a seasonal trend of decreasing bottom temperatures.

North of the Bight, variation of the water temperature in the Gulf of Maine (Gulf intermediate water is a source of water for the cold pool.) is responsive to oceanic circulation in high-latitude regions. Part of this circulation, the Scotian Current (a part of the water-mass that compensates northward moving water mass in the Gulf Stream), flows past Cape Sable into the Gulf of Maine. This current is a cold low saline flow that carries runoff from the St. Lawrence River. It contributes to the seasonally varying cyclonic gyre of the north-central part of the Gulf of Maine. Gulf circulation has larger southerly currents along the western shore in spring caused by seasonal maximums of river runoff. These inflowing water masses into the Gulf of Maine contribute to low Gulf salinity and maintenance of relatively low water temperature.

Mid-Atlantic Sea Level

Sea level changes are not expected to be the most significant consequences of global climate change in the Bight because of relatively large slopes of coastal land areas. The effect of water level on circulation within estuaries may cause important environmental changes that will not be reported here.

Change in Bight-area sea level is associated with change in the earth's surface elevation, wind stress, and water density change. Monthly average sea level records from tide gauges at Charleston, SC and Sandy Hook, NJ (Thompson, 1990) have relatively large annual variation. This is attributable to geographic orientation of the coastal areas relative to the seasonal wind direction changes.

At stations north of Rhode Island, less than half of the annual variability in sea level has been attributed to winds and atmospheric pressure (Thompson, 1990). At Charleston and Sandy Hook (stations where the coast is oriented in the direction of prevailing summer wind) sea level is influenced by wind (Thompson, 1990). Sea level change has been associated with changes of the Gulf Stream (Blaha, 1984) in shelf areas south of the middle Atlantic Bight. Since some Gulf Stream changes are correlated with large-scale wind fields (Godshall, 1990), association of any specific cause of long-period (i.e. interannual) sea level change is obscured.

Sea level along the middle Atlantic coast rose 10cm over the period 1930-1970 (Meade and Emery, 1972) but components of the change were not resolved in this source. Sea level rose about 10cm in the period 1950-75 at Sandy Hook but local differences are expected because of the local circulation. Annual variation of sea level on the shelf near the mouth of Chesapeake Bay was estimated to be about 17cm; minimum sea-level height corrected for atmospheric pressure effect occurs in spring and maximum heights occur in fall (Montgomery, 1938). The rate of sea level rise is about twice the rise on the west coast and annual variations are less than those generally observed on the west coast. Largest rates of change, by comparison, occur along the northwestern Gulf coast (Hicks et al.,1983).

Mid-Atlantic River Runoff

There is an annual variation of salinity on the shelf region of the mid-Atlantic Bight that is caused by annual variation in river runoff. The seaward salinity gradients from the surface in-flows of fresh water are affected by transient in-drifts of saline slope-water which may intrude to regions of the 20m isobath. The in-drift water mass is separated from the on-shelf water mass by oceanic salinity fronts that bring local change in water column sediment loading and chemical concentrations with salinity change. Stratification is variable; it is dependent upon the amount of surface in-flow and the occurrence of wind events to force vertical mixing of the water column (Bumpus, Lynde, and Shaw, 1973). The stratification of near shore water mass, caused by seaward flows of fresh water, is at a maximum in mid to late summer in the vicinity of Chesapeake Bay and other fresh water sources.

Since variation in evaporation and moisture content of saturated air is directly related to the air temperature, a local change of air temperature may be related to precipitation changes. The lack of correlation between temperature and precipitation change trend (Hanson et al., op. cit) over the United States as a whole may result from precipitation change dependence on moisture advection as well as other parameters. A change of temperature of the 19 year period average 1950-68 compared to the temperature average from the period 1931-49 was about -1° C in the region of the Delaware River water shed. Concomitantly, the precipitation in the relatively cooler 1950-68 period decreased about 0.5mm per day in the water shed (Karl and Riebsame, 1989). Runoff into the mid-Atlantic bight from the Potomac, Delaware, and Hudson River watersheds is illustrated in Figure 6. by the graph of gauged flow rates from selected stations within these watersheds. Although the runoff rates from the periods beginning in the 1970's are large, the rates are not large relative to preceding decades. An 11 year period of variability is a significant feature of these records. Such changes in runoff effect water quality in embayments of the Bight (Officer et al., 1984).

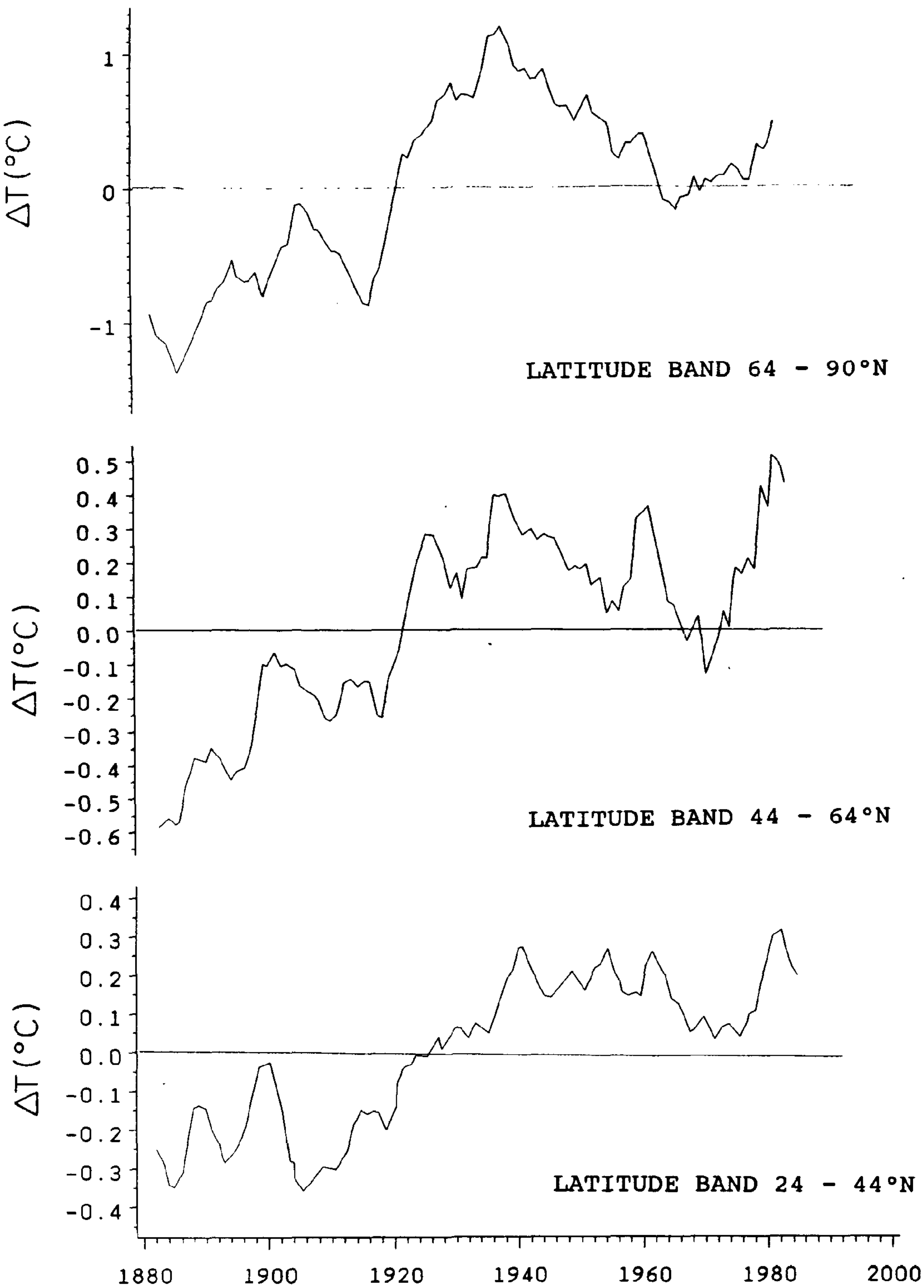

Figure 5. Northern Hemisphere Surface Air Temperature Variations Averaged for Selected Latitude Bands (Hansen and Lebedeff, 1987).

1.3.2 Northwest Gulf of Mexico

The runoff and siltation from the Mississippi/Atchafalaya rivers are dominant control sources for the coastal palustrine system. The bays of the coastal margin are important parts of the system because of biota that they support. Therefore, the environmental response of these areas to climate change could be described in relation to the coastal ecosystem biota. However, the orientation of this report to physical parameters of change directs these analyses primarily to the coastal physical responses.

Northwest Gulf of Mexico Circulation

The circulation on the northwestern shelf of the Gulf of Mexico is quasi-independent of the general circulation in the western Gulf basin. An independent, on-shelf circulation is established because the width of the shelf (over 200km to the 100m depth) and shallowness tend to isolate the shelf water mass from the dynamics of the deep water circulation regimes of the western basin. The coastal boundary of the shelf is uniformly arcuate with offshore barrier islands and relatively featureless bottom where bathymetric slopes are in the order of 1:1000. These characteristics promote the maintenance of seasonally established shelf circulation (Cochrane and Kelly, 1986).

The shelf circulation of fall and winter is an apparent cyclonic gyre with peripheral flows parallel to the coastal bathymetry and the shelf break. Weakening of this cyclonic circulation in spring begins along the south Texas coast in association with seasonal development of a southerly wind regime. By mid-summer the south-wind forced anticyclonic circulation dominates the shelf with a small portion of the shelf, near the Mississippi delta, under a continuation of the cyclonic gyre. Cross-shelf bottom flow results from downwelling along the coast in association with the anticyclonic gyre (Snedden et al., 1988) and from tidal currents. With onset of northeasterly wind in fall, the cyclonic gyre is reestablished over the shelf. The near-shore component of the cyclonic gyre is accentuated by the westerly drift of the Mississippi and Atchafalaya river outflows. This near-shore drift and other fresh water inflows produce an across-shelf gradient of salinity and density stratification in near-shore water masses.

Fall and winter northeasterly wind is associated with weak anticyclones in Louisiana and in the southeastern states associated with westward extension of the Bermuda High. These northeasterlies become less frequent as the southerly wind regime of summer becomes dominant over the northern Gulf. A propensity for anoxic bottom-water development in spring and early summer is established by stratification; the seasonal runoff is large, the weak southerly wind regime does not force vertical mixing of the water and solar heating of surface water increases stratification. An occurrence of northeasterlies late in spring can be significant with respect to production of anoxic bottom water. Wind stress from the northeasterlies forces the near-shore fresh water to spread south and west over a larger part of the shelf area producing a larger area with stratified water and, therefore, increased possibility of anoxic bottom water development (Harper et al., 1981). Therefore, changes of the Bermuda High may effect wind over the northern Gulf and cause undesirable water quality changes.

Northwest Gulf of Mexico River Runoff

Physical characteristics of the shelf environment are expected to respond to climate variations that change the rate of discharge of fresh water from the Mississippi and Atchafalaya rivers. The Mississippi watershed (Figure 7., Page 19) covers most of central United States. This very large area carries runoff that has, effectively, integrated over the short time (hours) and space scales of myriad precipitation events within the central plains region. During the period 1950 to 1968, precipitation of the U.S. Central plains areas increased by about 0.25 mm/day (concomitantly with a temperature decrease of about 1° C) compared to the period 1931-49. This represents an increase of about 13.5% for a representative station, Concordia, Kansas, based on U.S. Weather Bureau (1930) precipitation statistics. From regression analysis on precipitation data and stream gauged runoff (Karl and Riebsame, 1989), changes of runoff were expected to increase in the Mississippi water shed. However, the flow rate at Vicksburg, Mississippi gaging station decreased relative to the comparison period, 1931-49 (Figure 8., Page 20). During the 1970's, larger flow rates at Vicksburg were associated with larger amount of precipitation (Hanson et al., op. cit). The 1970's increases in runoff also occurred from the Appalachians (Figure 6., Page 18).

Northwest Gulf of Mexico Sea Level

Sea level change in the northern Gulf of Mexico over the past few decades has been largely caused by coastal land subsidence. Largest rates, about 0.63 cm per year in the vicinity of Galveston, TX (Hicks et al., 1983) are attributed to removal of gas and petroleum resources from coastal wells. This rate of change is not representative of the northern Gulf coast as a whole. Other factors causing change are steric effects and river runoff rates.

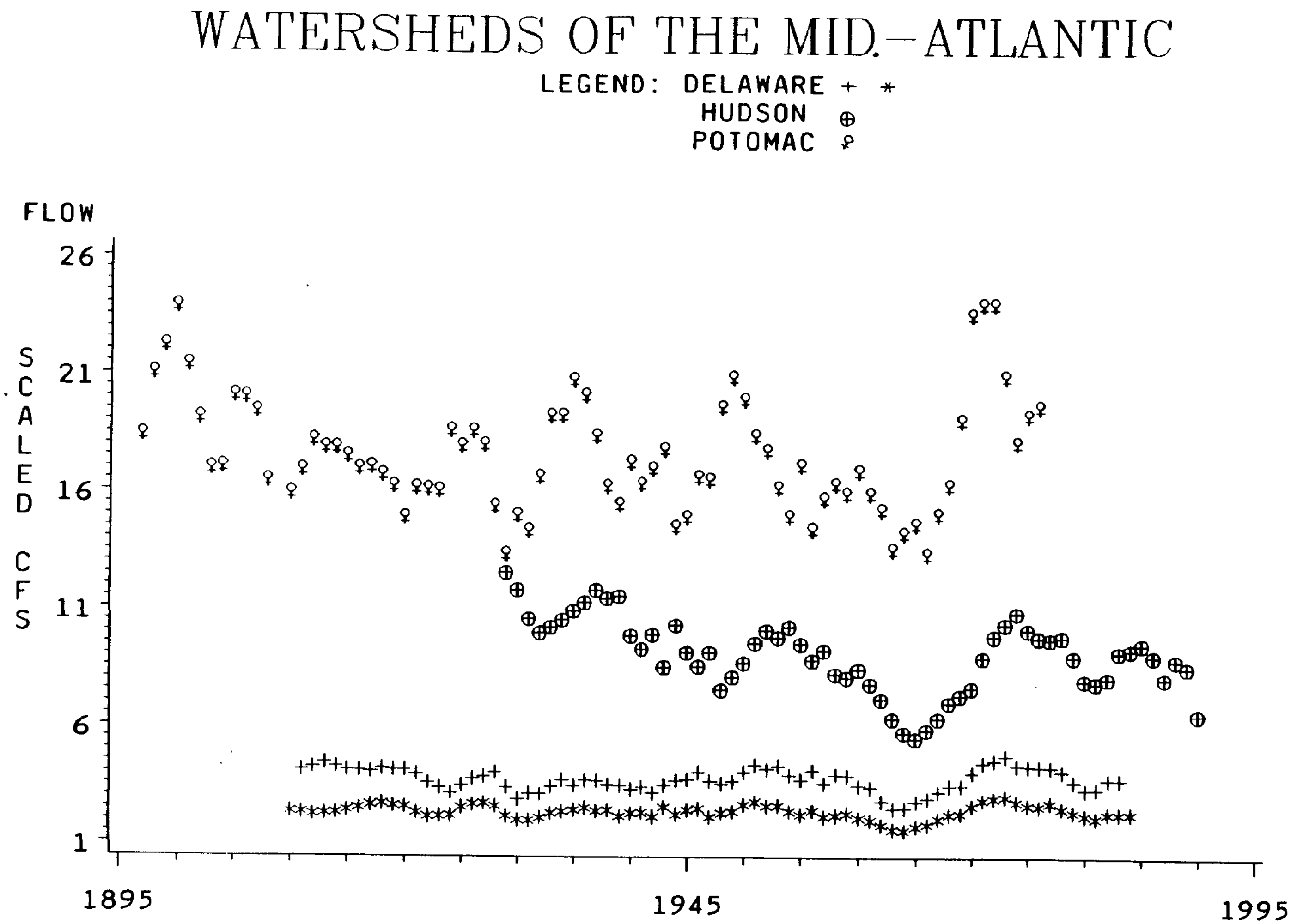

Figure 6. Runoff Rates from the Potomac River (Point of Rocks guage), Delaware River (Wallenpaupack and Bush Kill Creeks), and Hudson River (Rondout Creek) Watersheds. Annual Means of Guaged Flow are Smoothed by a 5-year Running Mean.

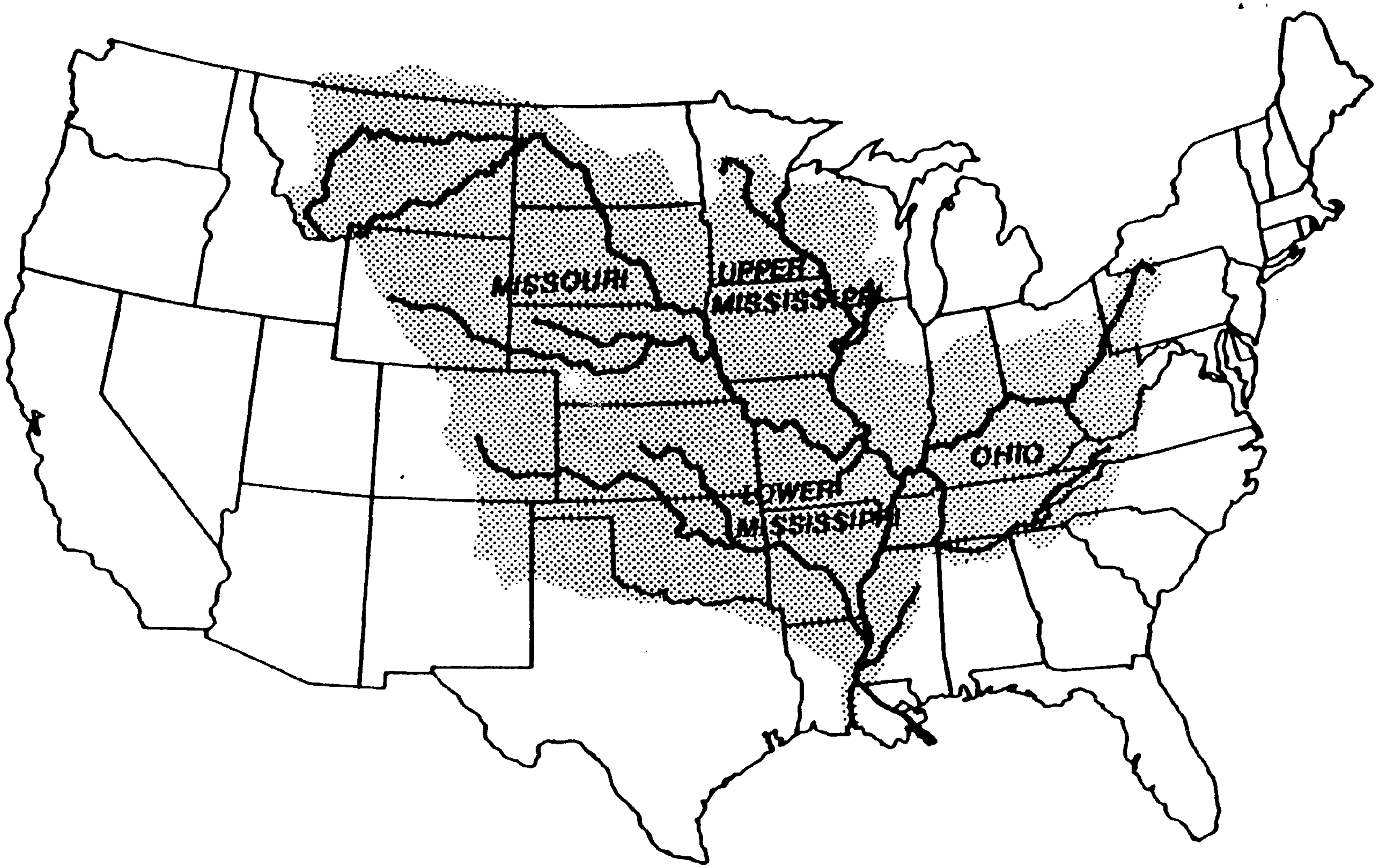

Figure 7. The Mississippi River Watershed (N. Rabalais and D. Boesch, 1990: EPA Coastal Ocean Physics Workshop, Jan. 8-9, 1990, Galveston, Texas, illustrations by R. E. Turner).

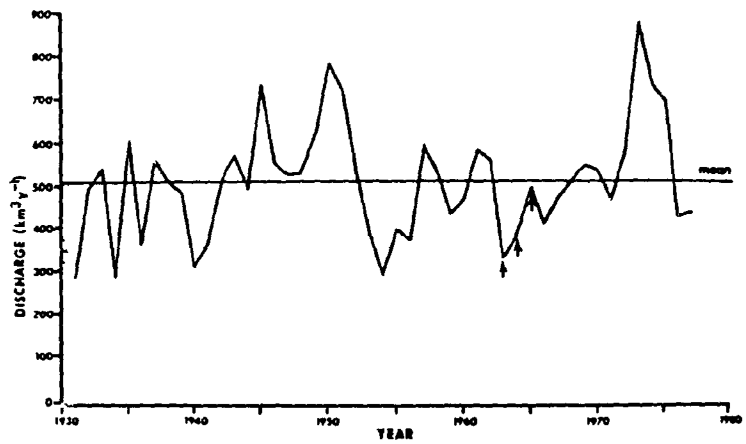

Figure 8. Annual Discharge of the Mississippi River, Measured at Vicksburg, MS 1931-1977 (Dinnel and Wiseman, 1986).

1.3.3 Southern California

Southern California is addressed here as the coastal area south of San Francisco. The area is chosen as an analog of western-coastal responses because of the sensitivity of the marine circulation to broad-scale wind regimes associated with the Hadley Circulation.

Southern California Ocean Circulation

The California shelf width is narrow, about 6km out to 100m depth, but about 110km to the 2000m isobath off San Francisco and about 260km to the 2000m isobath off San Diego. Because of the narrow shelf width north of Point Conception, this near-shore area is exposed to deep-water wave and current regimes (Godshall and Williams, 1981). In the Southern California Bight, the Channel Islands and wider shelf protect the coast.

North of Point Conception, an oceanographic trough of dynamic depth is oriented along the mid-shelf isobaths in winter and seaward of the Channel Islands of Southern California. This trough position is synoptic with surface near-shore northward currents. In spring the trough is contiguous with the coast, through the Bight and north to Cape Mendocino and northward surface currents in the near-shore areas cease.

The north flowing Davidson Current in the near-shore area north of Point Conception is a winter circulation feature on the surface that is synoptic with a deep-water northward flow, the California Undercurrent, in mid-shelf. These currents transport a warm, saline water mass northward.

The surface layer southward flowing California Current is a feature of mid and outer-shelf regions that is poorly defined in winter but well organized in spring and summer. This wind-driven current brings cool, low-saline waters southward. The near-shore portion of California Current has a seaward component caused by Ekman transport that is identified with upwelling along the coast.

In the Southern California Bight, surface near-shore drift is northward in late fall and early winter; it leads the transition to winter seasonal-circulation of the shelf, north of Point Conception. Transition toward southerly flow in early spring is, apparently, a combination of weakening in a cyclonic circulation eddy south of Point Conception and shoreward movement of the California Current system. Shoreward of the Channel Islands, in the area between Santa Barbara and north to Pt. Conception, the cyclonic eddy may exist in any month and this produces variable northerly drift at the shoreline. In early fall, the flow inshore of the channel islands returns northward, that is a surfacing of the California Undercurrent in the Bight.

Local circulation is strongly influenced by submarine canyons in the southern California shelf area. These canyons, e.g. Santa Monica Bay, cause spatially varying currents from tide and wind forcing which result in eddies. Eddies cause local changes in vertical stirring of the water column and local variations in water temperature (Leipper, 1955). Kelp beds affect water temperature on beaches from Pt. Conception southward by sheltering beaches from cool water of the California Current (Kolpack, 1971).

Southern California Atmospheric Circulation

The general ocean circulation along the coast is forced by broad-scale wind regimes with local modifications from sea-breeze circulation. Therefore, appreciation for potential impact on the coastal environment must include some explanation of the prevailing wind regimes.

Wind is northerly along the California coast and seasonally variable, primarily with respect to speed. Seasonal change occurs with change in the eastern Pacific Subtropical Anticyclone, a ridge of high pressure over northwestern United States, and a low pressure area in southwestern United States that is produced from thermal effects. Change in the subtropical anticyclone is inversely associated with change in the Aleutians-area low pressure (the Aleutians Low). Since the California Current is wind driven, the seasonal variation in wind is associated with seasonal variation in coastal circulation and water temperature.

In winter the Aleutians Low deepens, the subtropical anticyclonic area decreases and moves southward, and the ridge of high pressure in the Northwest may become contiguous with a weak ridge that replaces the summer-low in the Southwest. The decrease and southward migration of the Pacific subtropical anticyclone is synoptic with southward migration of the polar front. Storms, developed along the front, may move into California coastal areas. Northerly wind along the coast is, relative to other seasons, more variable (wind constancy is about 20-40%). In the Southern California coastal-bight, wind from interior high pressure areas subsides from elevated land areas to produce a dry seaward flow of air (DeMarris et al., 1965).

In summer, the Pacific subtropical anticyclone is seasonally largest; it extends northward over the latitude of Hawaii and eastward to coastal California. A low pressure area commonly develops from surface heating in southwestern United States. The coastal northwesterly wind is seasonally strongest and consistent in direction. Wind constancy (ratio of vector and scaler means) is about 80-90%. In the Southern California coastal bight, shoreward of the Channel Islands, wind is variable and influenced by a sea-breeze circulation.

Seasonal atmospheric circulation along the U.S. west coast is readily associated with broad-scale atmospheric circulation and interhemispheric changes (Dickson and Livezey, 1984). In the eastern Pacific, low-latitude regions circulation changes are correlated with pressure anomaly in the north Pacific (Bjerknes, 1969; Namias, 1985). However, the specific processes producing correlation between latitudinal change of circulation on these scales are unknown. Long period change in wind along the U.S. west coast, such as increased coastal wind stress 1946-1988, was deduced through water temperature changes (Bakun, 1990). These temperature changes are typically produced on eastern oceanic boundaries from wind effects. A period of cool water temperature along the southern California coast in 1955 was produced with buildup of the east Pacific High and intensified northerly wind. The subsequent shift to warmer water in 1957 (Figure 9., Page 24) was accompanied by a weakened high and deepened Aleutian Low. The weakened northerly winds were accompanied by a simultaneous warming of air temperature but the warming was not interpreted as caused by warmer coastal water (Namias, 1960). At the same time there was a substantial rise in sea level (Stewart, 1960).

Local modifications to the northerly winds produce locally varying water temperature. In Santa Barbara Channel, the land-sea breeze regime produces a southwesterly wind at the shore that backs to a westerly or northwesterly wind further offshore. This local wind affects the amount of upwelling that may result in warmer coastal water because of opposing circulation from wind stress. The offshore northerly winds cause upwelling and cooler surface waters with the result that there is a complicated and variable pattern of water temperatures across the shelf. Santa Monica Bay is a trap for locally advected warm water as well is the Ventura embayment. Headland sheltering of the embayments also produces locally unique coastal water circulations which affect water temperatures. As a consequence of these local patterns of water temperature, there is considerable coastal variation in climate effects from fog and low stratiform clouds.

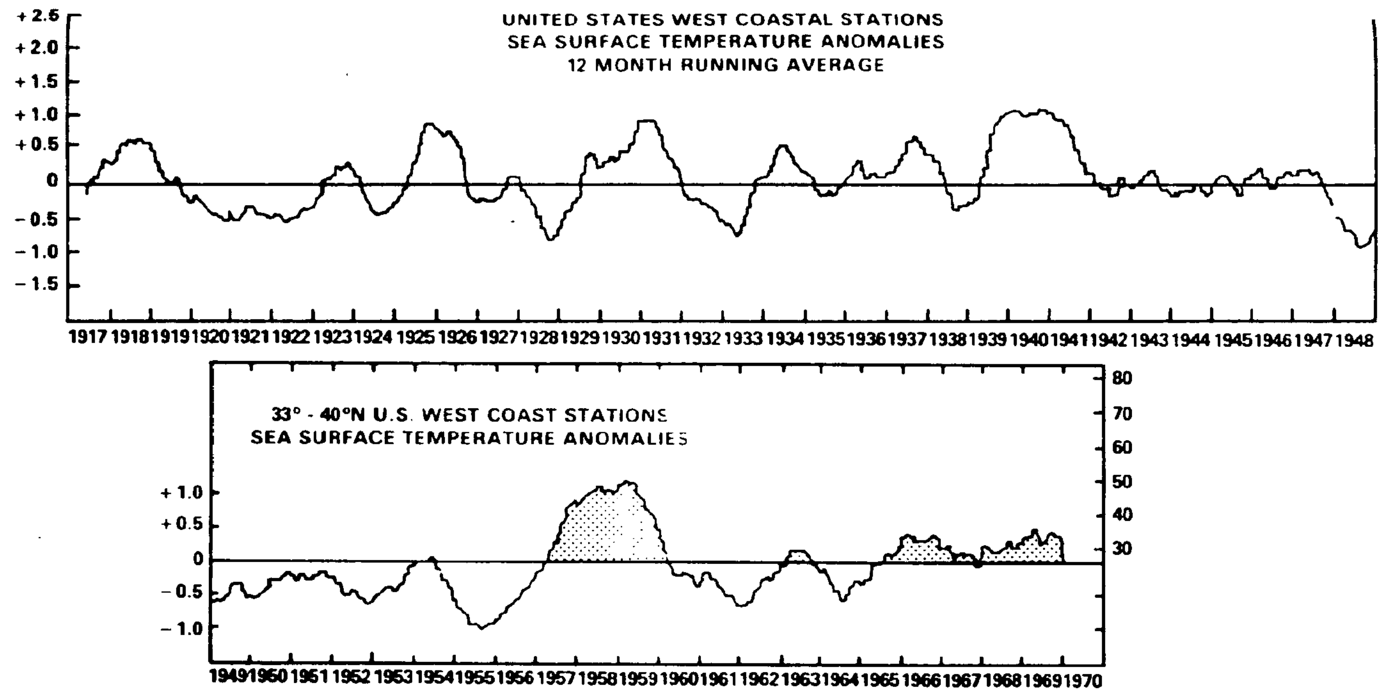

Figure 9. Sea Surface Layer Temperature Anomaly (°C) of the U.S. West Coast (analysis by Godshall and Williams, 1981).

Southern California River Runoff

Variation of precipitation and land runoff from the coastal area of southern California correlates with broad-scale pressure distribution over the north Pacific. The Arroyo Seco river flow rate, for example, is negatively correlated with pressure anomalies in the north-central Pacific region (Cayan and Peterson, 1989; Namias, 1980). However, the correlations are relatively weak and increased runoff, expected during the 1957 period of weak coastal pressures, did not occur in all major rivers of the study region, e.g. the flow rates of the Sacramento, Merced, and the Arroyo Saco rivers graphed by Cayan and Peterson (op. cit). Longer temporal-scaled variations of the pressure and associated runoff changes are found in all rivers of the region. Changes in precipitation/river-runoff onto the coast are illustrated by the gauged flow rate records of the Arroyo Saco river (Figure 10., Page 26). Seasonal changes in runoff rates are also expected due to early-season snowmelt with warmer climate (King et al., 1990).

River runoff into the Southern California Bight influences beach configuration by supplying sedimentary material distributed along the coast. Large runoff events associate with increased concentrations of silicates in the near shore area of the Bight (Tibby and Terry, 1959).

Southern California Sea Level

The average of hourly measured water elevations over yearly periods is defined as the annual mean sea level. Along most of the California coast, mean sea level has been rising relative to sea level for the 1941-1959 National Tidal Datum Epoch with elevation rise of about 0.15 cm/year at San Francisco (Harris, 1979). Sea-level increase rate of 0.12 cm/year is reported over the period 1855-1922 at San Francisco (Smith and Leffler, 1980).

Coastal sea level varies seasonally with changes of more than 20cm over the year (Harris, 1979). Sea level variation caused by transient oceanographic conditions can be as much as 30cm (Smith and Leffler, 1980). Off San Francisco, sea level falls with the spring seasonal increase of the north-wind stress and surface cooling from upwelling. South of Point Conception, sea level decreases occur in late winter and decreases are more variable in magnitude. Assuming that the change of California coastal water temperature is proportional to the upwelling and decreased coastal sea level, change of coastal water temperature from the early 1900's to 1970 (Figure 9., Page 24) suggests that sea level has had large fluctuations in the past. Since 1917, sea water temperature change shows no long-period trend of temperature and, therefore, there is no evidence to suggest a long period change in upwelling along the coast. However, there was a 3.6cm decrease in sea level over the period (Huang, 1972).

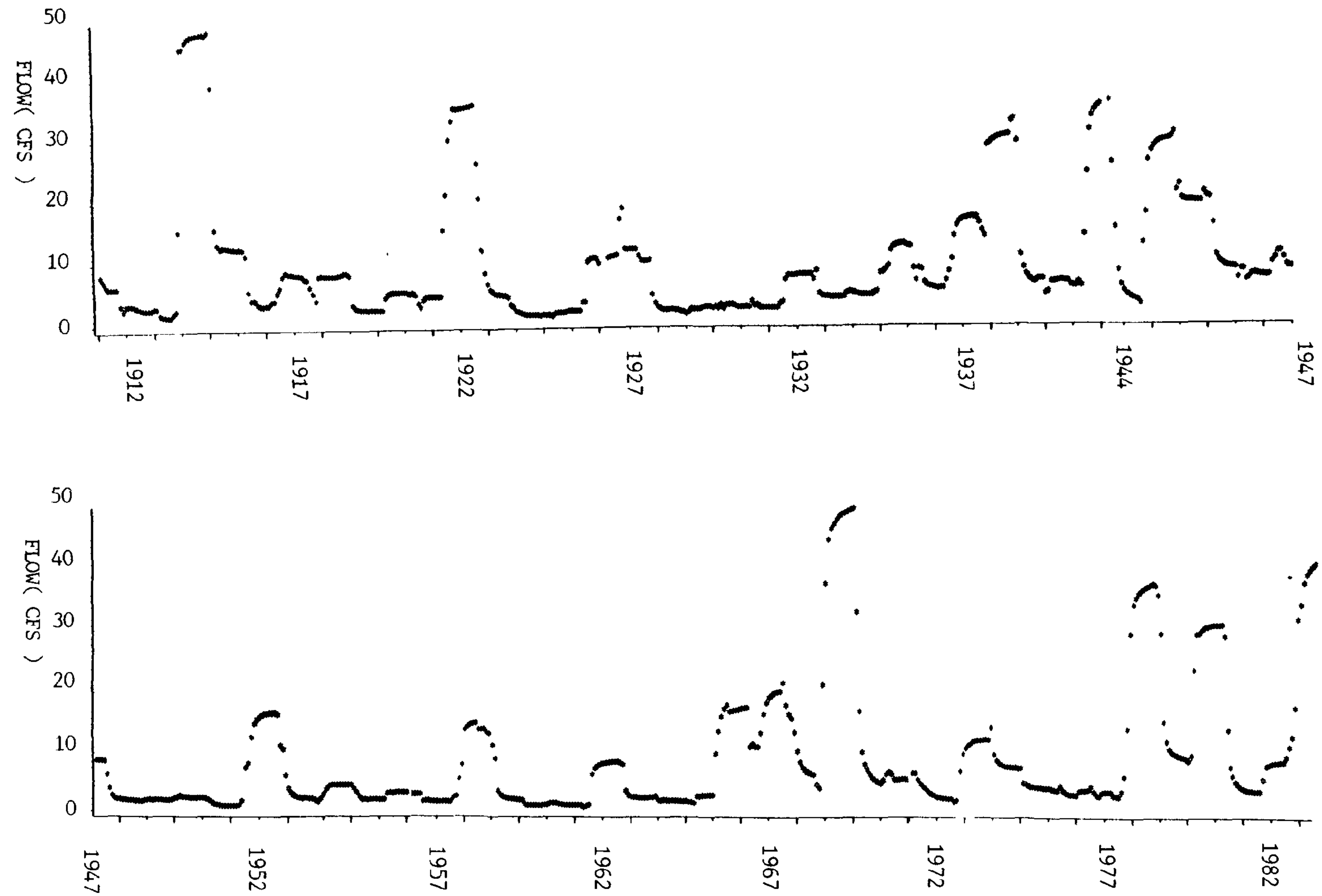

Figure 10. Monthly Mean Flow Rate of the Arroyo Saco River Smoothed by a 12-Month Running Mean.

Graphs of water temperature from San Diego and Los Angeles show water temperature increased during the period of climate cooling (from about 1945) when coastal wind and upwelling were expected to decrease (Figure 11., Page 28). However, the temperature record from may be influenced by local process that are not typical in other coastal areas of California. The seasonal variation in sea level produced by atmospheric pressure variation is about 4cm in the San Diego, CA area and seasonal variation is out of phase with seasonal heating and cooling cycles. This is interpreted as evidence of influence from the broad-scale geopotential surfaces that are established by the major oceanic circulation patterns (Reid and Mantyla, 1976). Therefore, rise in water temperature need not be interpreted as a decrease in coastal upwelling.

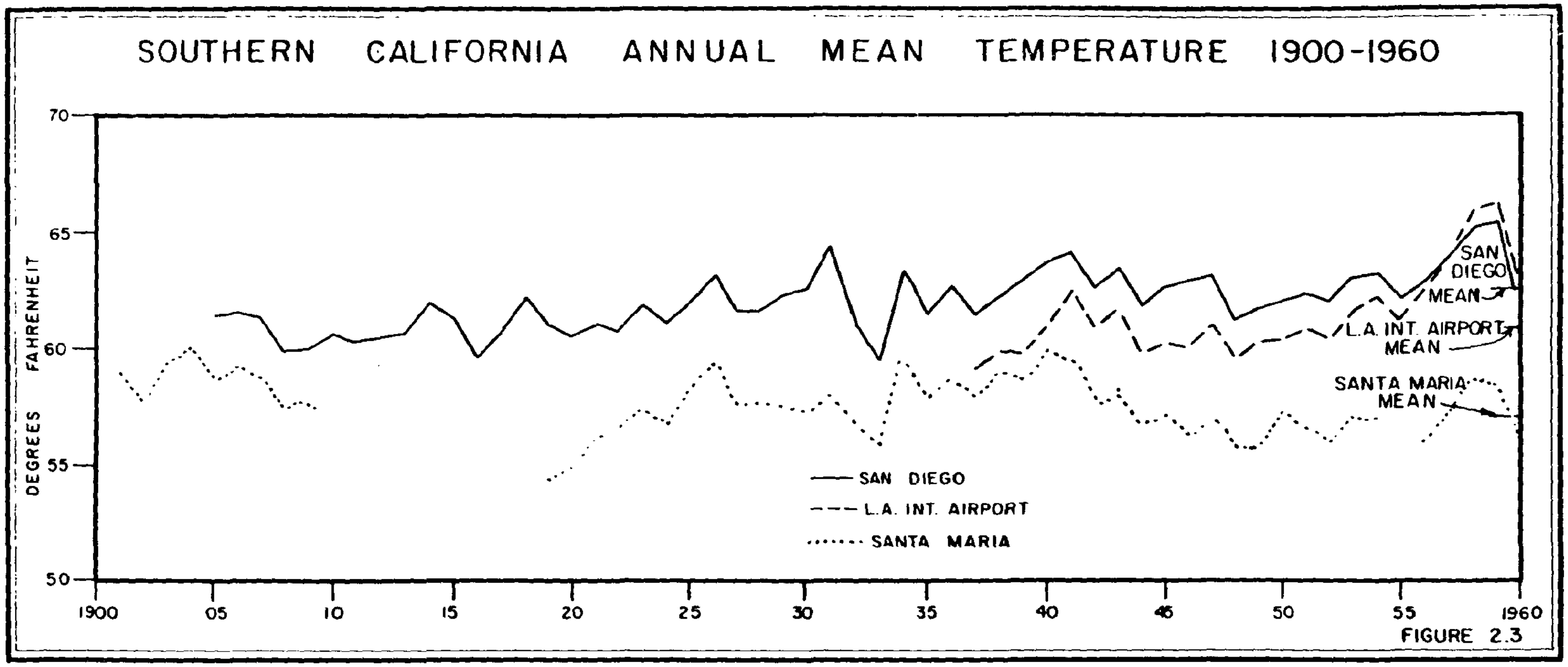

Figure 11. Water Temperature of Coastal, Southern California (California State Water Quality Control Board, 1965).

2. MODEL PREDICTION OF CLIMATE

General Circulation Models (GCMs) used for assessing possible effects of climate change operate with the same application of the laws of fluid dynamics as the models for meteorological forecasting (Hansen et al., 1983). Although GCMs will not provide forecasts of meteorological variables that are extensions of the usual commercial forecast periods, GCMs can produce balanced distributions of energy/energy fluxes and fluid mass related to predicted atmospheric forcing. These distributions result from simulation of ocean and atmospheric processes by analogues of the actual environmental processes and, therefore, they require validation that is commonly provided by the climate at 1 X CO_2. Modeling technology research seeks improved process generalizations of the atmosphere and oceans that reduce requirements for process rate specification and data (Grassl, 1988). Spatial scales for modeling are sought to optimize model results relative to input data requirements. During the present time, modeling operations also are limited by computing capability and accurate specification of surface fluxes of moisture, heat, and momentum. The effects of these limitations are commonly evaluated by creating a model output of the climate of the present (the 1 X CO_2 climate) that can be compared to observations.

Definition of climate change, with a doubled carbon dioxide concentration in equilibrium with all parts of the environment, is a basis for modeling result intercomparison (Figure 12., Page 30). These latitudinal temperature distributions show agreement within the compared modeling result; the temperature of the latitudes of the United States are predicted to increase relative to the temperatures of the equatorial region with atmospheric carbon dioxide concentration doubled. However, the time for earth's atmosphere to reach a doubled carbon dioxide concentration is poorly estimated because the rate of approach to equilibrium of carbon dioxide in the atmosphere with the concentration in the oceans varies as the rate of carbon dioxide increases. Carbon dioxide uptake by oceans is inversely proportional to atmospheric carbon dioxide rate of increase, i.e. halving the rate of increase will double the time for the ocean uptake to reach equilibrium with the atmosphere (Grassl, 1988). Also political and social factors governing the rates of carbon dioxide increase are unknown.

The most important parameters of climate with sensitivity in modeling of climate are those used to characterize atmospheric radiation balances. Since carbon dioxide influences radiation balances, the concentration of atmospheric carbon dioxide is theoretically an important parameter. Cloud amount and atmospheric water vapor are as important as carbon dioxide in causing climate change. That places the parameters related to surface flux of water vapor to be important also (Hartmann, 1984). Doubled carbon dioxide model runs by the Goddard Institute of Space Science (GISS) model (Hansen et al., 1984) predicted increased air temperature of the United States and coastal areas (with increases of about 3° to 5° C).

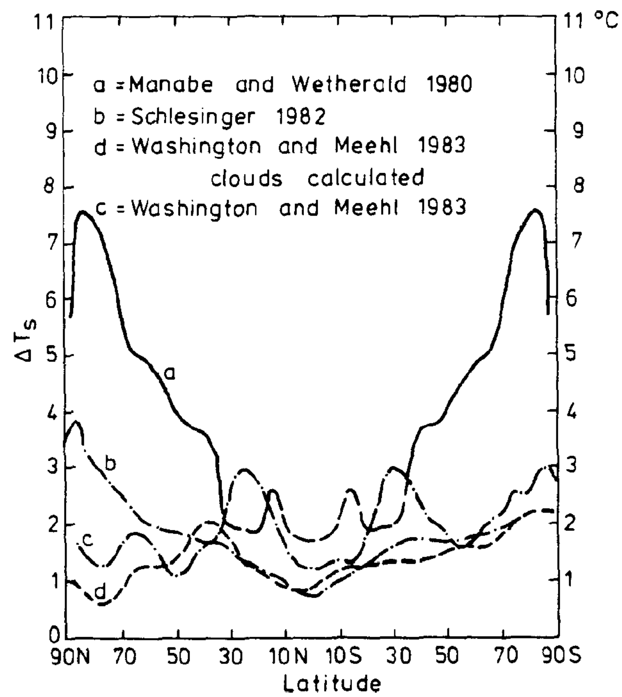

Figure 12. Longitudinal Mean Temperature Changes Predicted by GCMs Under Doubled Atmospheric Carbon Dioxide Concentration (Grassl, 1988).

The prediction of large coastal temperature increases are predicated on a cloud model that leads to decreased low and middle-level cloud with increased convection. Some argument might be offered to counter this assumption in coastal regions with cold surface water. Evaporation increases nonlinearly with temperature which leads to larger vapor pressure increases relative to temperature increases. Increased water vapor in surface air-mass that may be advected over cold water surface is expected to lead to increased low-level clouds.

Positive temperature feedback from increased water vapor concentration is approximately compensated by negative feedback from lapse rate changes. Therefore, cloud effects are control factors for local temperature changes. Coastal low-level stratiform cloud are produced over water areas where there are cold water surfaces and, since these cold surface waters commonly develop from wind-forced upwelling, the GCM must be coupled to coastal oceanic circulation simulation. The accurate coupling of oceanic circulation and atmosphere is also important for GCM predictions of climate in the coastal areas of the United States where low-latitude Hadley Circulation influences climate.

Numerical experiments using the ECMWF (European Center for Medium Range Weather Forecasting) general circulation model (Cubasch, 1985) demonstrated association of enhanced Hadley Circulation with mid-latitude atmospheric dynamics. Enhanced Hadley Circulation, a consequence of positive temperature anomaly in the equatorial Pacific, led to Aleutian Low deepening and higher pressure over the area of eastern maritime Canada. Positive surface pressure anomalies in the Pacific are correlated with increased size of the Bermuda High and this change of pressure distribution is an expected result of an enhanced Hadley Circulation.

2.1 Interpretation of Modeling Results

Figures 13a. and 13b., Pages 32 and 33, are vector averaged winds predicted by the NOAA, General Fluid Dynamics Laboratory (GFDL) GCM model (Jenne, 1989; Manabe and Wetherald, 1987) for August with atmospheric carbon dioxide concentration of the present (1 X CO_2) and with atmospheric carbon dioxide concentration doubled (2 X CO_2). A comparison of the analyses shows strengthened southerly wind components in the Gulf of Mexico are predicted during 2 X CO_2 conditions (Appendix C and Figure 14.). Water-mass circulation on the northwestern shelf of the Gulf of Mexico is normally under the influence of the summer southerly wind regimes (ab in'tra 1.3.2 Northwest Gulf of Mexico) and, therefore, little change may be expected in the anticyclonic circulation of water on the shelf.

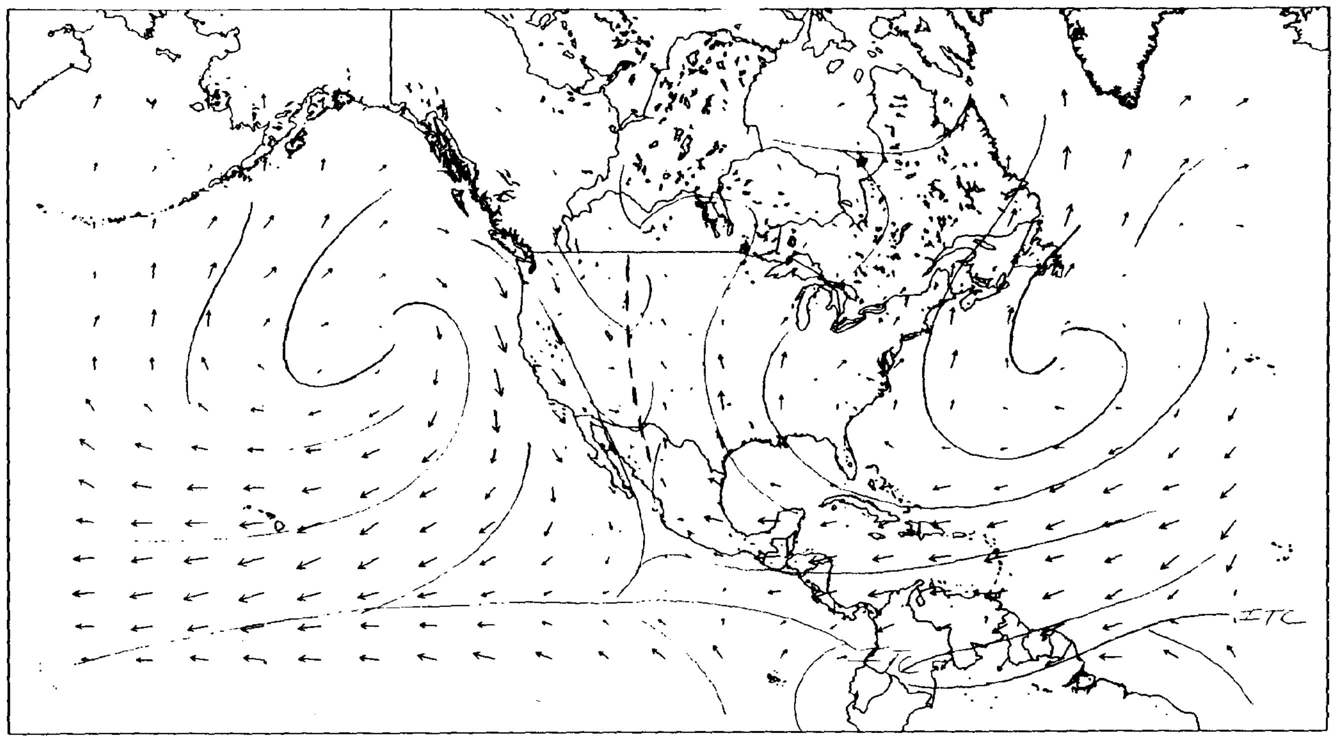

Figure 13a. August Wind Vectors Estimated by Numerical General Climate Model for an Atmosphere with CO_2 Concentration of the Present.

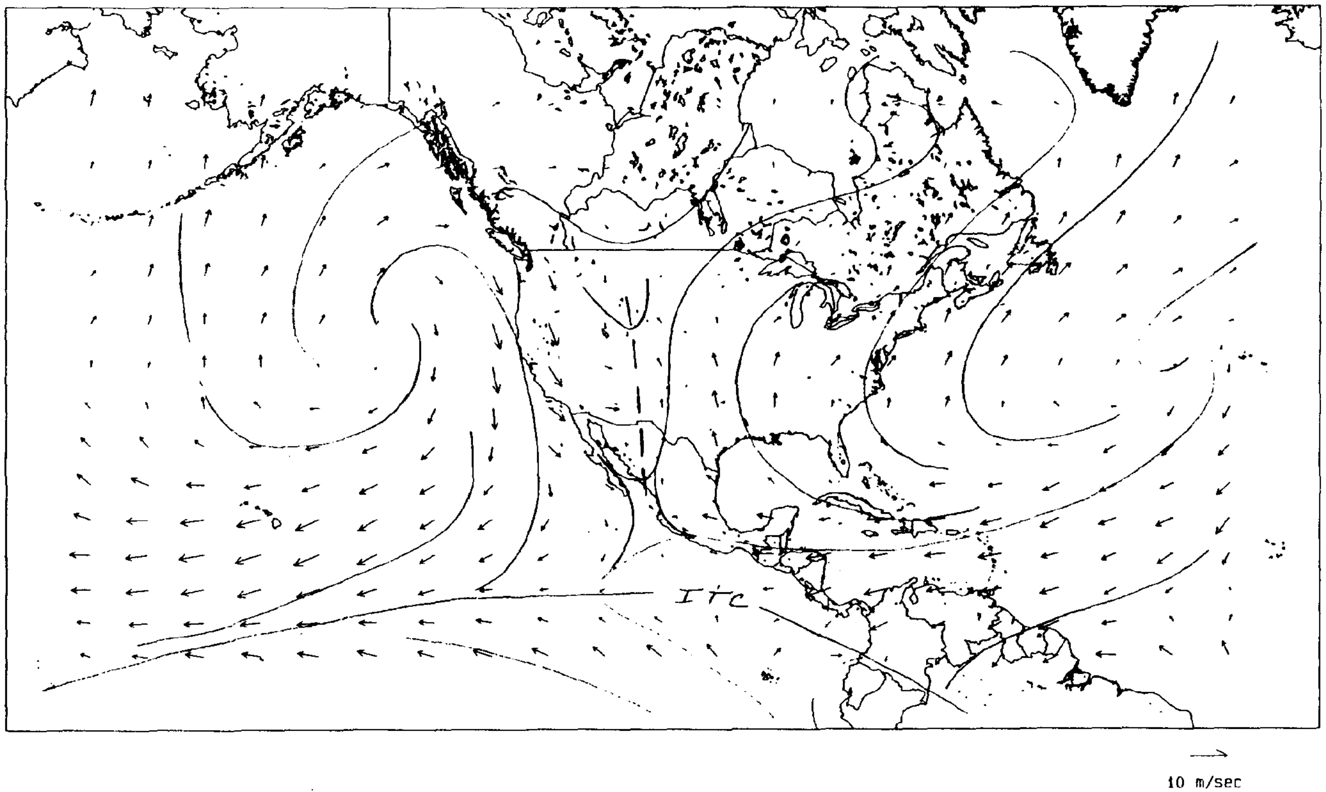

Figure 13b. August Wind Vectors Estimated by Numerical General Climate Model for an Atmosphere with Double the CO_2 Concentration of the Present.

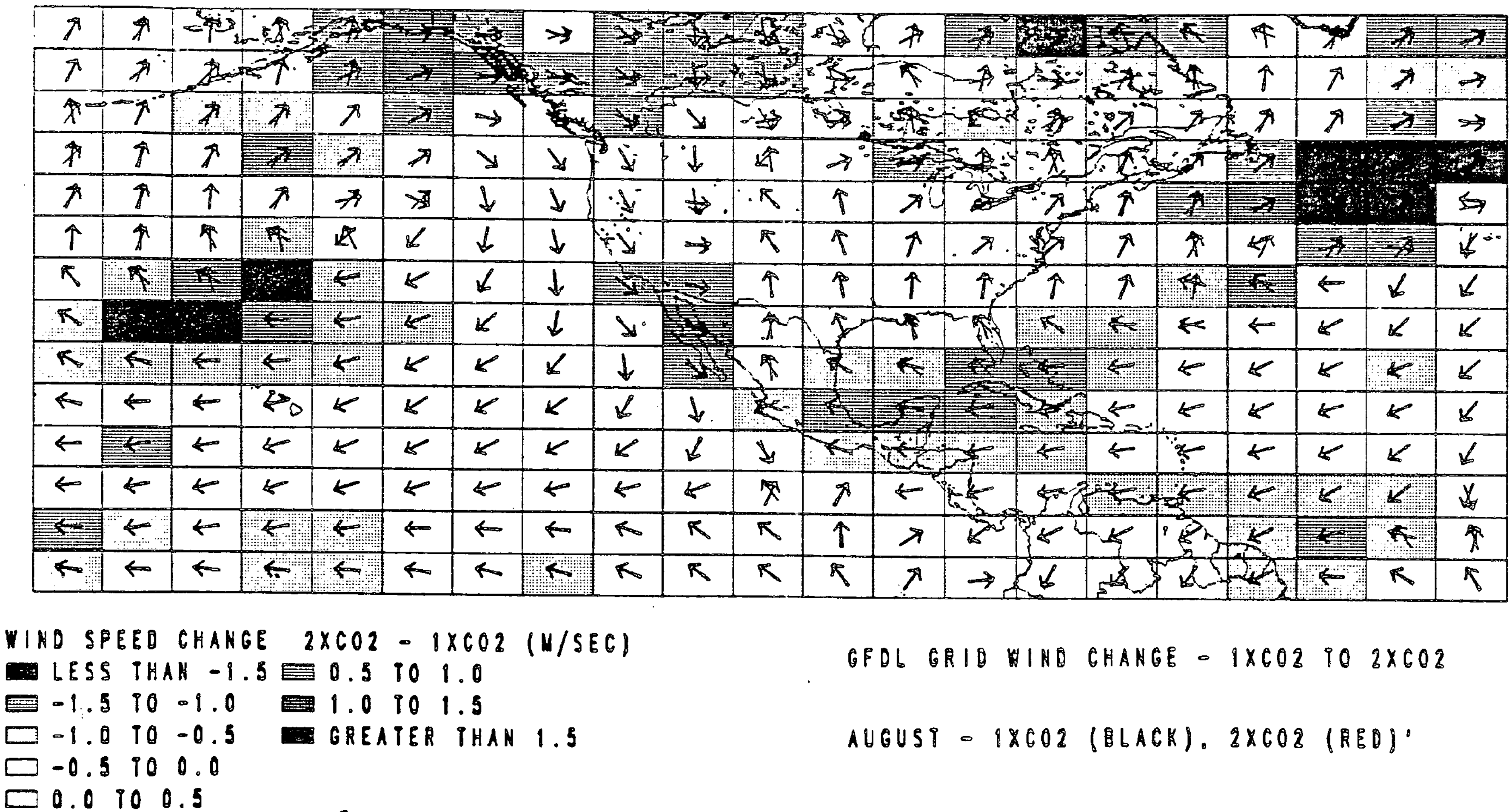

Figure 14. Comparison of Model Predicted Surface Wind from an Atmosphere with 1 X CO_2 and with 2 X CO_2 Concentrations in August (NOAA GFDL Q-Flux Model Runs, 1988).

Moisture advection into continental United States will be increased and this may result in increased precipitation amounts with possible increased river runoff. However, increased continental temperatures will increase evaporation and decrease runoff. In the past, increased flow rates of the Mississippi and Atchafalaya Rivers into the Gulf have increased areas of stratified coastal water masses and this has lead to anoxic bottom water problems on the shelf. Possible increases in runoff volumes under 2 X CO_2 could lead to similar anoxic bottom water problems following runoff events as occurred in the past. United States east coast August wind regimes, predicted by the 1 X CO_2 (Figure 13a.), are similar to the winds shown by the mean wind field on the COADS derived analysis (Appendix C.), winds are southerly along the coast. These winds produce coastal upwelling (ab in'tra 1.3.1 MID-ATLANTIC BIGHT).

Figures 15a. and 15b., Page 38, show the GFDL GCM predicted wind fields of January for 1 X CO_2 and 2 X CO_2 respectively. The 1 X CO_2 wind fields are similar to the monthly mean wind fields derived from COADS (Appendix C.). However, the 2 X CO_2 fields are different on the east coast of the United States from the winds of the present times. The predicted changes are associated with change in the Bermuda High; winter coastal winds are forecast to be more southerly on the coast (Figure 16.) with veering in southern coastal areas. This is likely to cause coastal upwelling in winter and this could lead to warmer and more saline water along the coast in winter. In an analysis of the GFDL model-forecasted 2 X CO_2 precipitation over the United States (Finkelstein and Truppi, 1990), much of the seasonality of precipitation distribution of the present climate is lost over the mid-west and eastern states areas. This agrees with expectations deduced from moisture flux associated with westward extension of the Bermuda High in winter. Although predicted wind speed will increase for a 2 X CO_2 atmosphere, the increases are about an order of magnitude less than wind increases considered by Lantham and Smith (1990) for significant increase of aerosol generation at sea.

Since GCMs commonly fail to produce the correct absolute mean atmospheric pressure on the surface (Gates et al., 1990), pressure distribution should be the parameter of analysis. All models reproduce the subtropical anticyclones but there is a range in the anticyclone central pressure (which is generally too high in the northern hemisphere) and there is variation in the position of the anticyclones latitudinally (Gates et al., 1990). However, the similarity of the wind fields on coastal United States when the 1 X CO_2 wind fields are compared to the wind fields derived from COADS indicates the GFDL predicted position of the Bermuda High must be correct. Therefore, the predicted wind fields under 2 X CO_2 should be a reasonable expectation.

The high pressures of the subtropical anticyclones produce large meridional pressure gradients in mid-latitudes. These gradients lead to strong westerly wind regimes that are sensitive to model representation of drag from mountain ranges (Slingo and Pearson, 1987). This could be of consequence in simulation of atmospheric circulation and precipitation patterns over central United States because of influences from the Rocky Mountains. However, comparison of the trough position deduced from mean continental pressure distributions (U.S. Navy, 1981) with the GFDL 2 X CO_2 pressure fields indicates the position is not predicted to change from that of the present.

GCMs predict temperature increases under conditions of doubled carbon dioxide of about 2° to 5° C in the mid-Atlantic Bight area. Figure 17., Page 40, gives estimates of runoff that will come from the Delaware River watershed with 2° C increase in temperature and with varying amount of precipitation change. These variations in runoff at different stations within the Delaware River estuary as predicted by the different GCMs is given in Figure 18., Page 40. In comparison with these predictions, the Goddard Institute for Space Study (GISS) model result is much different from both the General Fluid Dynamics Laboratory (GFDL) model and Oregon State University (OSU) model output.

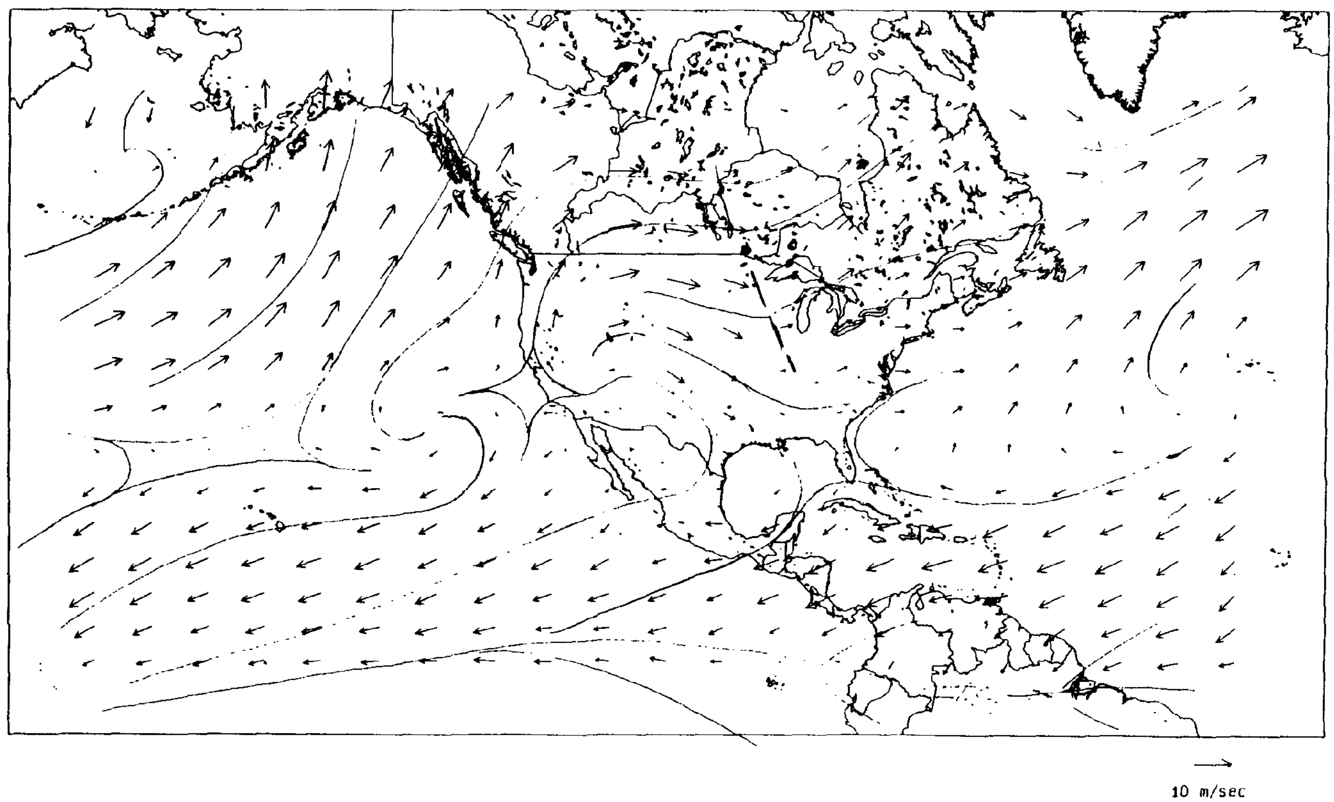

Figure 15a. January Wind Vectors Estimated by Numerical General Climate Model for an Atmosphere with CO_2 Concentration of the Present.

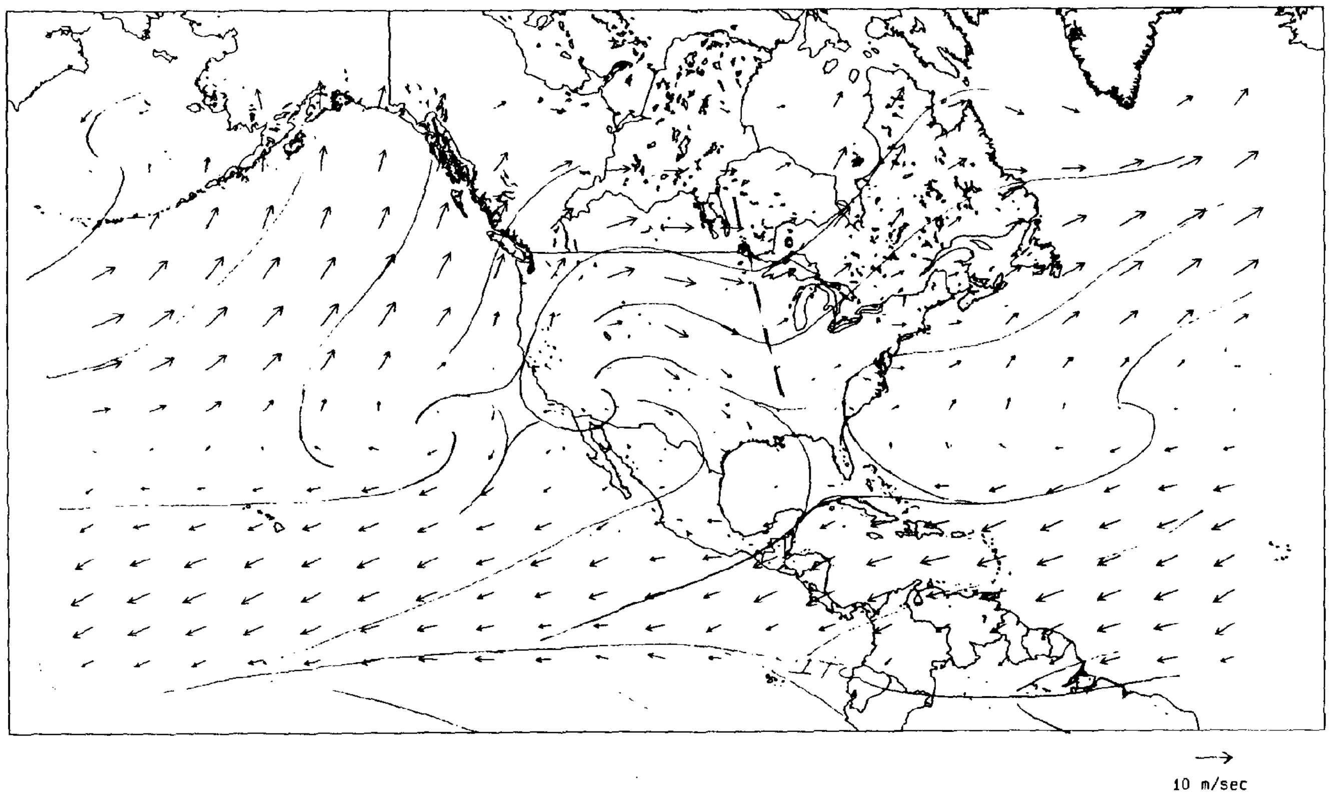

Figure 15b. January Wind Vectors Estimated by Numerical General Climate Model for an Atmosphere with Double the CO_2 Concentration of the Present (NOAA GFDL Q-Flux Model Runs, 1988).

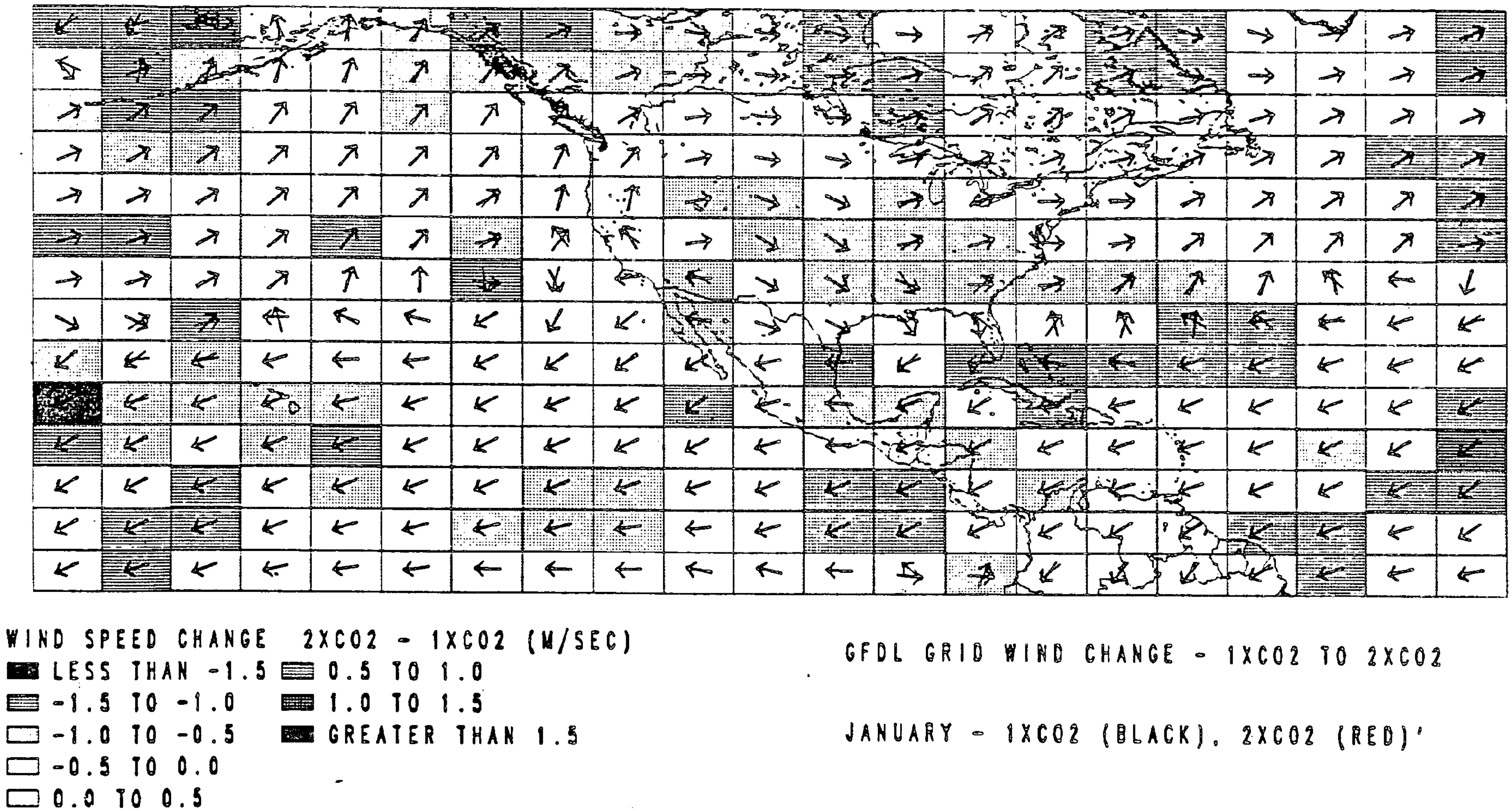

Figure 16. Comparison of Model Predicted Surface Wind from an Atmosphere with 1 X CO_2 and with 2 X CO_2 Concentrations in January (NOAA GFDL Q-Flux Model Runs, 1988).

Measurement Stations, Delaware River Watershed

	Montrose, PA	Trenton, NJ
Precipitation at Present,	P = 486	P = 381
	+2°C temperature change	
Precipitation Change (%)	.....runoff amount (mm)......	
P+20	632	501
P+10	532	411
P	411	329
P-10	351	258
P-20	268	188
	+4°C temperature change	
P+20	571	431
P+10	476	359
P	389	286
P-10	306	221
P-20	231	157

Figure 17. Estimated Runoff from the Delaware River Watershed With Increased Air Temperature and Precipitation Changes (mm) in the Watershed (M. Airs, 1990: Watershed Hydrology, Coastal Ocean Physics Workshop, Jan. 8-9, 1990, Galveston, TX).

	Measured Precipitation (mm)	General Climate Models GISS	GFDL	OSU
Montrose, PA	486	364	453	528
Trenton, NJ	381	245	353	397
Dover, DE	347	213	324	355

Figure 18. Model Predicted Runoff (mm) in the Delaware River Watershed for +2°C Climate Scenario (M. Airs, 1990: Watershed Hydrology, Coastal Ocean Physics Workshop, Jan. 8-9, 1990, Galveston, TX).

3. ANALYSIS FROM COADS:

The Comprehensive Ocean-Atmosphere Data Set (COADS) included wind and atmospheric surface-pressure monthly mean data (for 2° square geographic areas) from 1854 through 1979 (National Oceanic and Atmospheric Administration (NOAA), 1985). Means from the period of record (Appendix A) were mapped over the geographic area eastward from 130E to 10W longitude and in latitudes from the equator northward to 40N. These data provide the bases to which monthly means from specific periods are compared in production of difference analyses. Three periods within the COADS record period are selected for this study. The first period represents conditions associated with a trend toward warm temperature in the Northern Hemisphere prior to 1900. The second period, 1935-44, is a relatively warm climate that is followed by a cooling climate. The third period, 1970-79, is a period of cool temperature with a trend to warmer temperature (Figure 1b., Page 4). A hypothesis is set forth that cool and warm period variations in climate of the Northern Hemisphere are associated with global-scale circulation changes in atmosphere and oceans. The net wind of the study area is a westerly with annual average speed variations associated with warming and cooling climate. These changes of the broad-scale wind regimes is shown by a graph of wind speed over the period of COADS analysis, 1890-1979 (Figure 19). A component of the global-scale circulation is the Hadley Circulation (ab in'tra 1.2 ATMOSPHERIC CIRCULATION) which has features controlling atmospheric advection of moisture (therefore precipitation and river runoff control) over the United States and hence freshwater input to coastal regions.

3.1 Differences in Oceanic-Area Wind Regimes for Selected Periods

Low-latitude wind regimes are part of the Hadley Circulation and these winds change over time (Godshall, 1971). Differences in these regimes for selected periods are computed to explain effects of global-scale circulation changes on U.S. coastal areas. Periods of climate variation are commonly considered over time that includes many years; specific months or seasons from a year are not germane in analyses of climate variation. Our basic wind-difference components are developed by year and then grouped to represent the historical periods of interest in the cool and warm climate variations. Wind-difference components were computed with a procedure developed by F. Godshall and J. Jalickee (Williams and Godshall, 1977) that is described in Appendix B of this report. Wind-difference factors, nu and phi, are computed in comparison of pairs of wind vectors (the long-term mean wind for each month of each 2° averaging area and the monthly mean winds for the area and year). The nu values are the magnitude differences of the pairs for all months and phi values are the direction differences of the pairs. In the analyses shown in Figures 20a,b. through 22a,b., Pages 44 through 49, nu values are mapped by the use of open circles (meaning the decade winds were smaller than the long-term mean

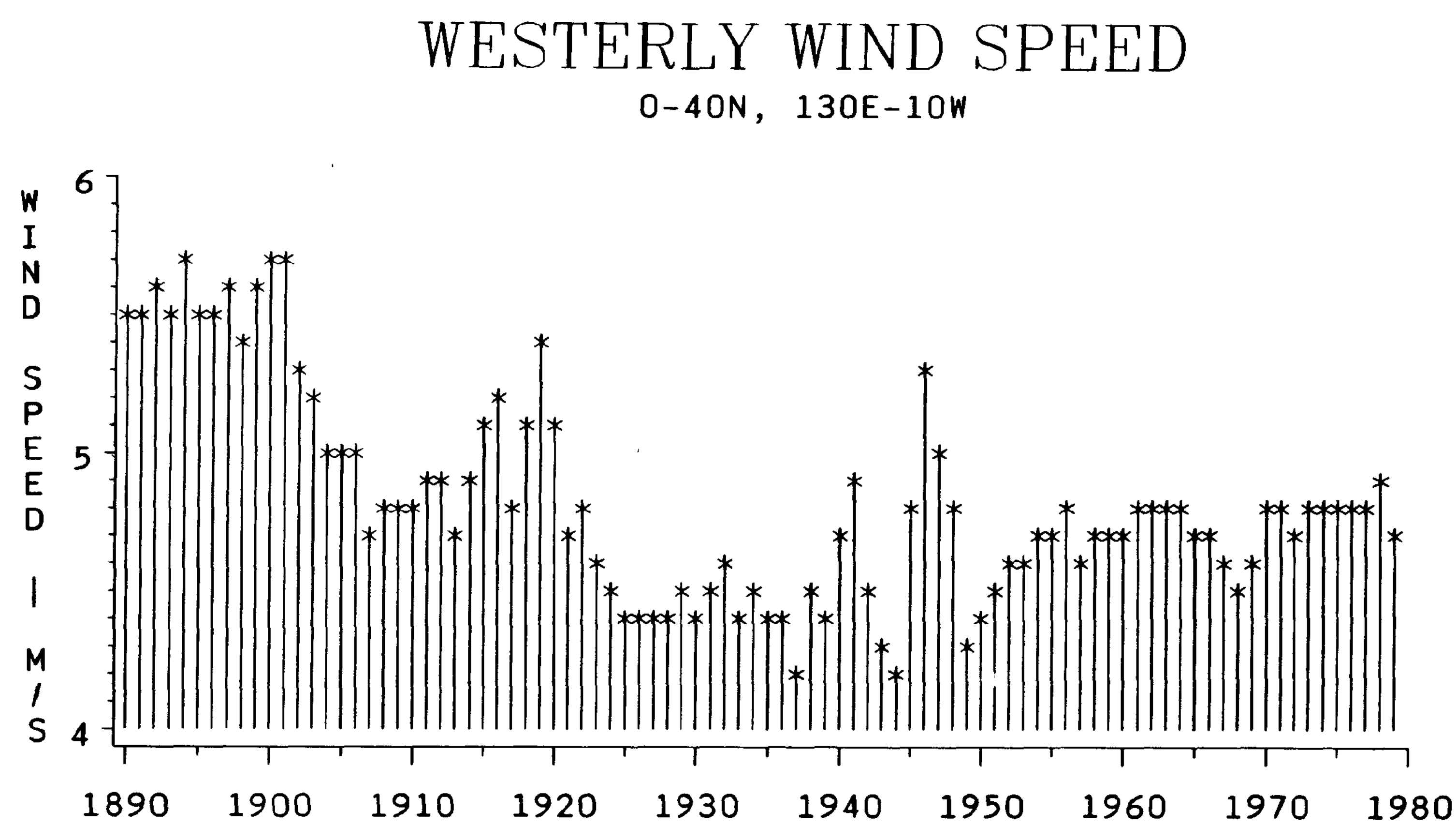

Figure 19. Wind Speed Variation from COADS Analysis over the Period 1890-1979.

wind in the 2° square area) or by shaded circles (meaning the decade winds were larger than the long-term mean wind). Phi values are mapped by the use of open circles (meaning the decade wind direction veered (rotated in a clockwise direction) relative to the vector averaged wind direction over the COADS record period) or by the use of shaded circles (meaning the decade wind direction of the 2° square area backed (rotated in a counter-clockwise direction) from the direction of the long-term average direction).

In reference to the annual mean temperatures of the northern hemisphere (Figures 1a. and 1b., Page 4) or the annual mean temperature of the United States (Figure 4., Page 9), temperature was relatively low in the late 1800's, high in the period 1935-1944, and low again in the period 1970-1979. Wind summary periods are selected from these periods to intercompare the characteristics of the wind fields in these periods and to relate wind circulation to the known coastal and continental climate conditions. Figures 20a. and 20b., Pages 44 and 45, are produced from COADS monthly wind averages, over 2° square areas, in the years 1889 through 1899. These maps show the surface winds along the United States coasts to be veered from the long-term average and, generally, of larger speed. Figures 21a. and 21b., Pages 46 and 47, are similar analyses for the period 1970 through 1979. The coastal winds are again generally veered from the long-term average and of larger speed and these conditions again preceded a warmer climate. Wind characteristics from the period 1935-1944 are mapped in Figures 22a. and 22b., Pages 48 and 49. During this period the winds are backed from the long term mean direction in United States Coastal areas and, generally, lower speed. These circulation conditions preceded climate cooling. Veering and turning southward with strengthening of coastal winds is predicted by the GFDL 2 X CO_2 wind field (Figures 13a,b. and 15a,b., and Appendix C), an expected circulation associated with climate warming based on COADS. However, these COADS analyses results show some differences over the coastal regions with some veering and backing occurrences in all analysis periods.

Wind effects on oceanic circulation on the coast of California (ab in'tra SOUTHERN CALIFORNIA OCEAN CIRCULATION) are changes of upwelling and coastal water temperature. The COADS analysis period 1935-1944 is within the coastal water-temperature anomaly records shown in Figure 9., Page 24. From these records, the result of wind direction backing and decreased speed during the 1935-1944 period was increased coastal water temperature. Temperature anomaly was equal to about +0.23° C over the decade. The records of measured sea-level south of San Francisco (Chelton et al., 1982) also support the expectation of less upwelling along the coast during the decade (Figure 23., Page 50); sea-level is of the highest recorded that indicates weak southward transport of surface water mass. Conversely, the expected result of the wind regimes of the late 1800's and 1970's is for colder coastal temperature.

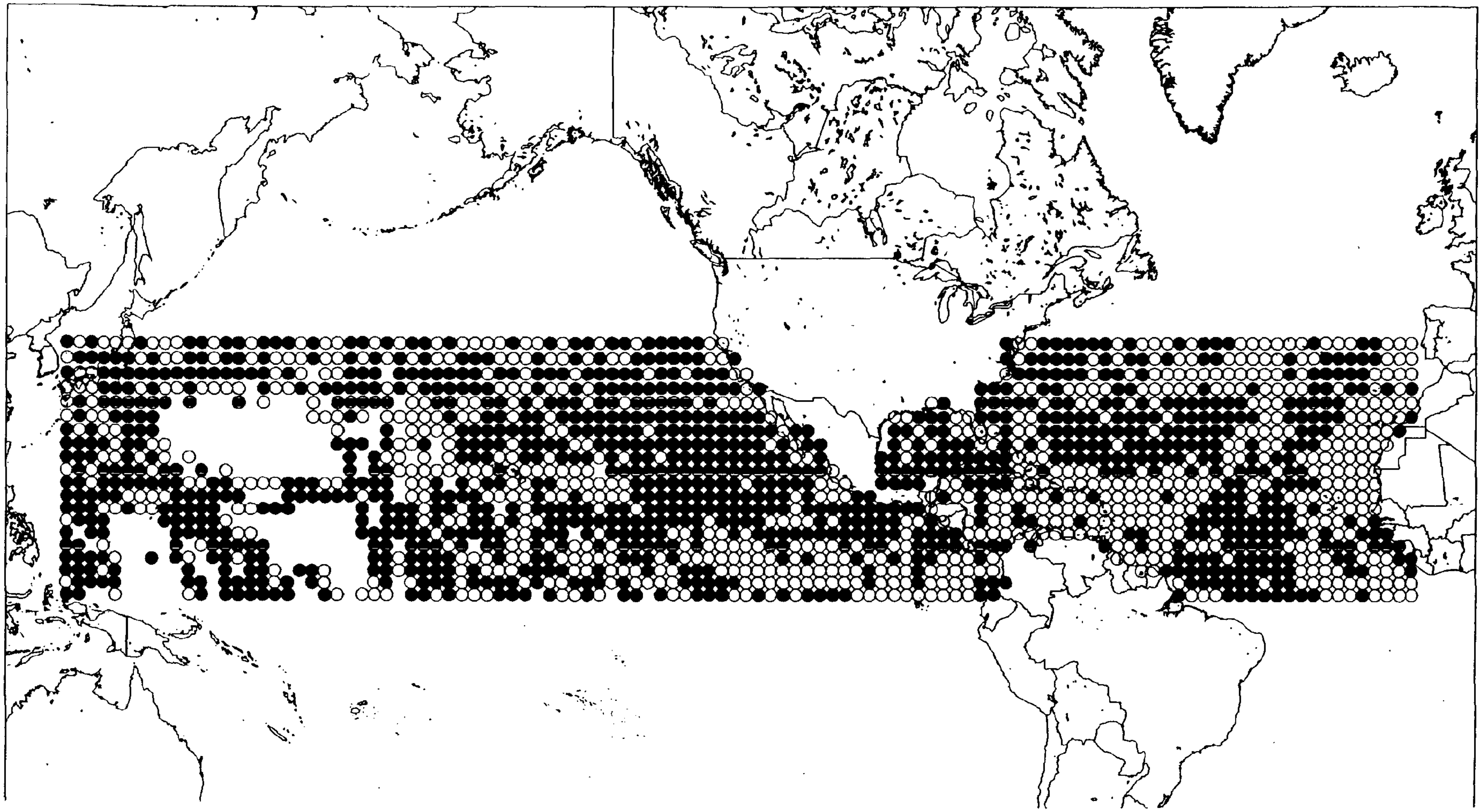

Figure 20a. Wind Speed Anomaly for the Period 1889-1899 Computed from COADS (Shaded Circles Indicate Larger, Open Circles Indicate Smaller).

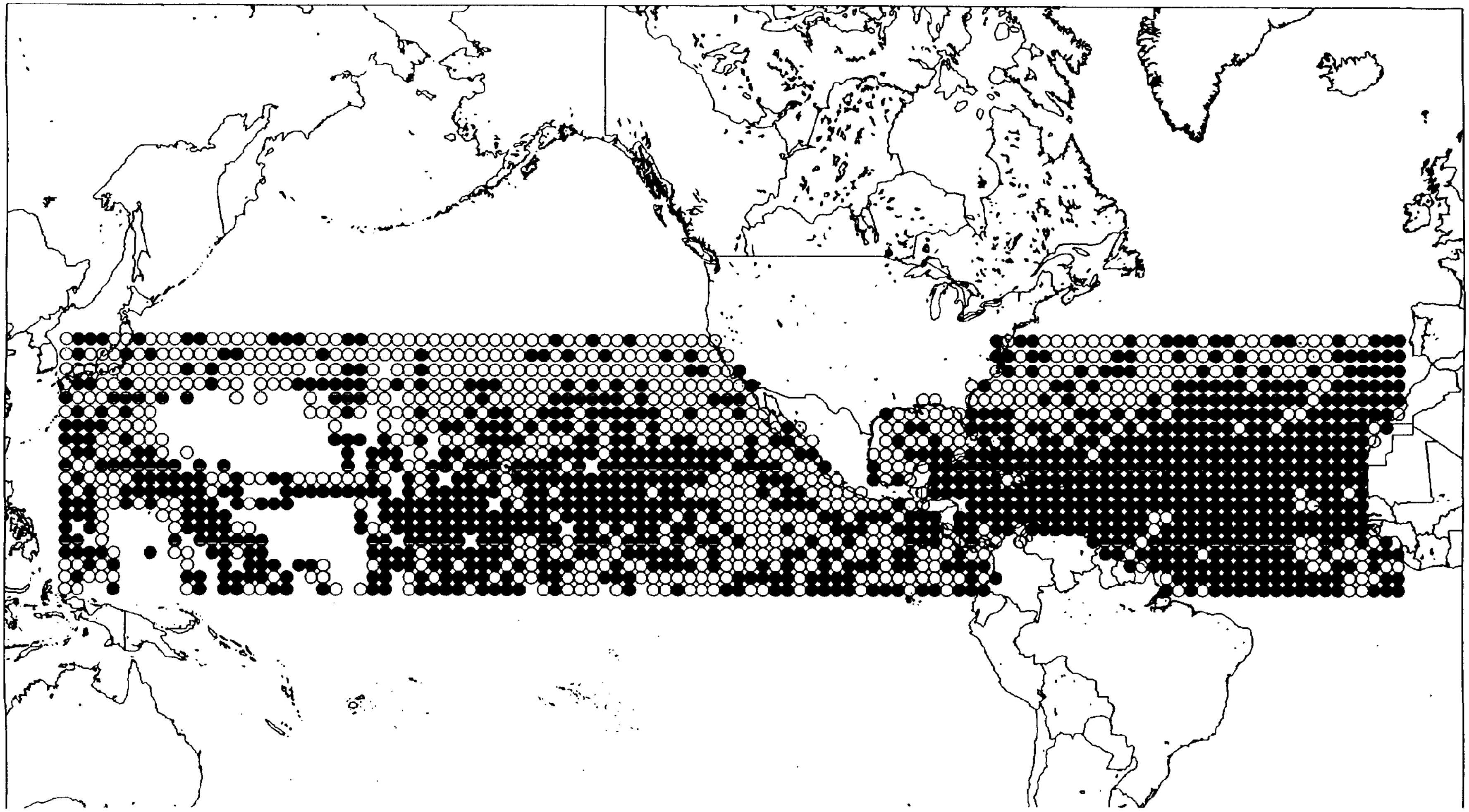

Figure 20b. Wind Direction Anomaly for the Period 1889-1899 Computed from COADS (Shaded Circles Indicate Backing, Open Circles Indicate Veering).

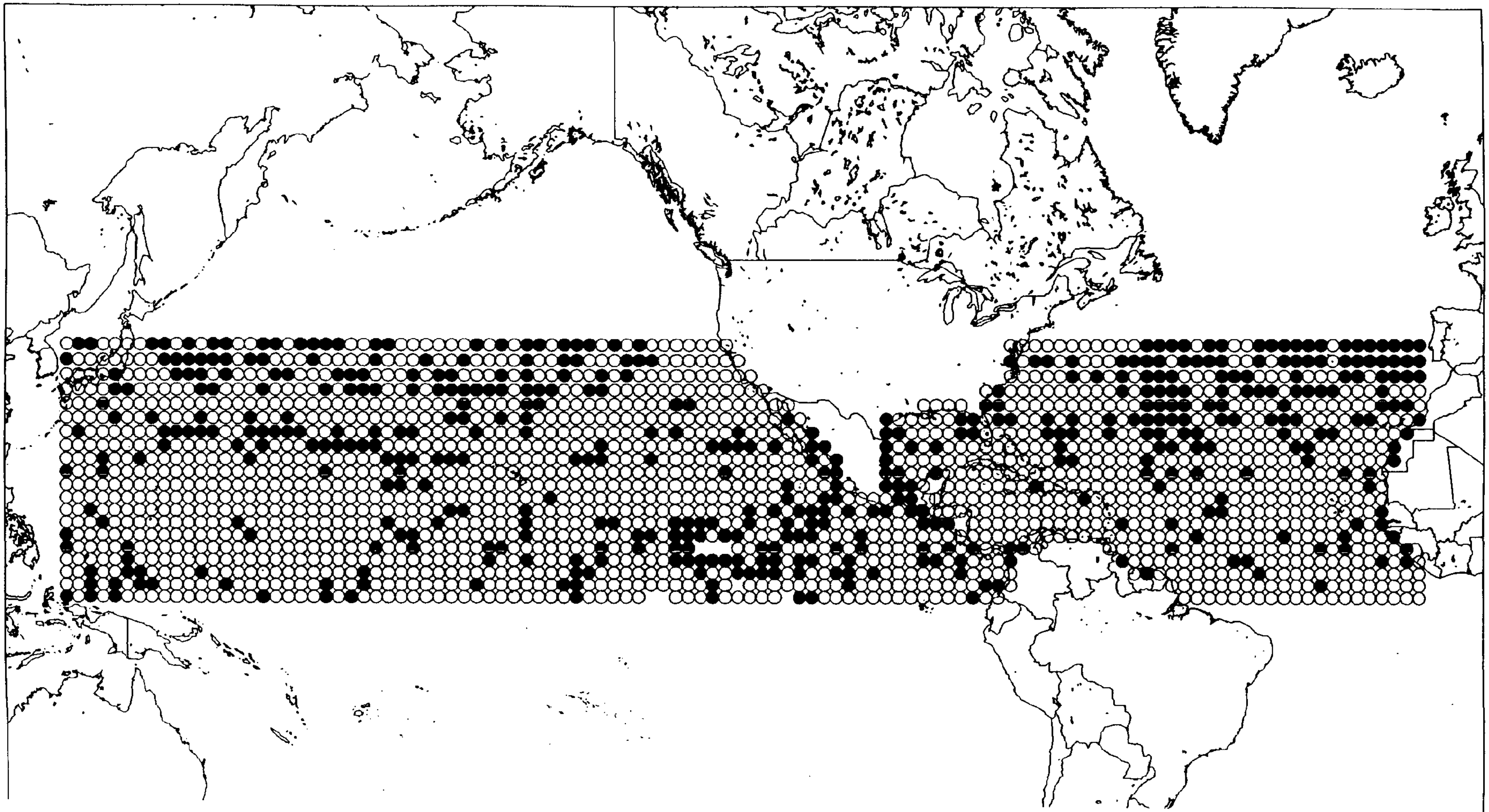

Figure 21a. Wind Speed Anomaly for the Period 1935-1944 Computed from COADS (Shaded Circles Indicate Larger, Open Circles Indicate Smaller).

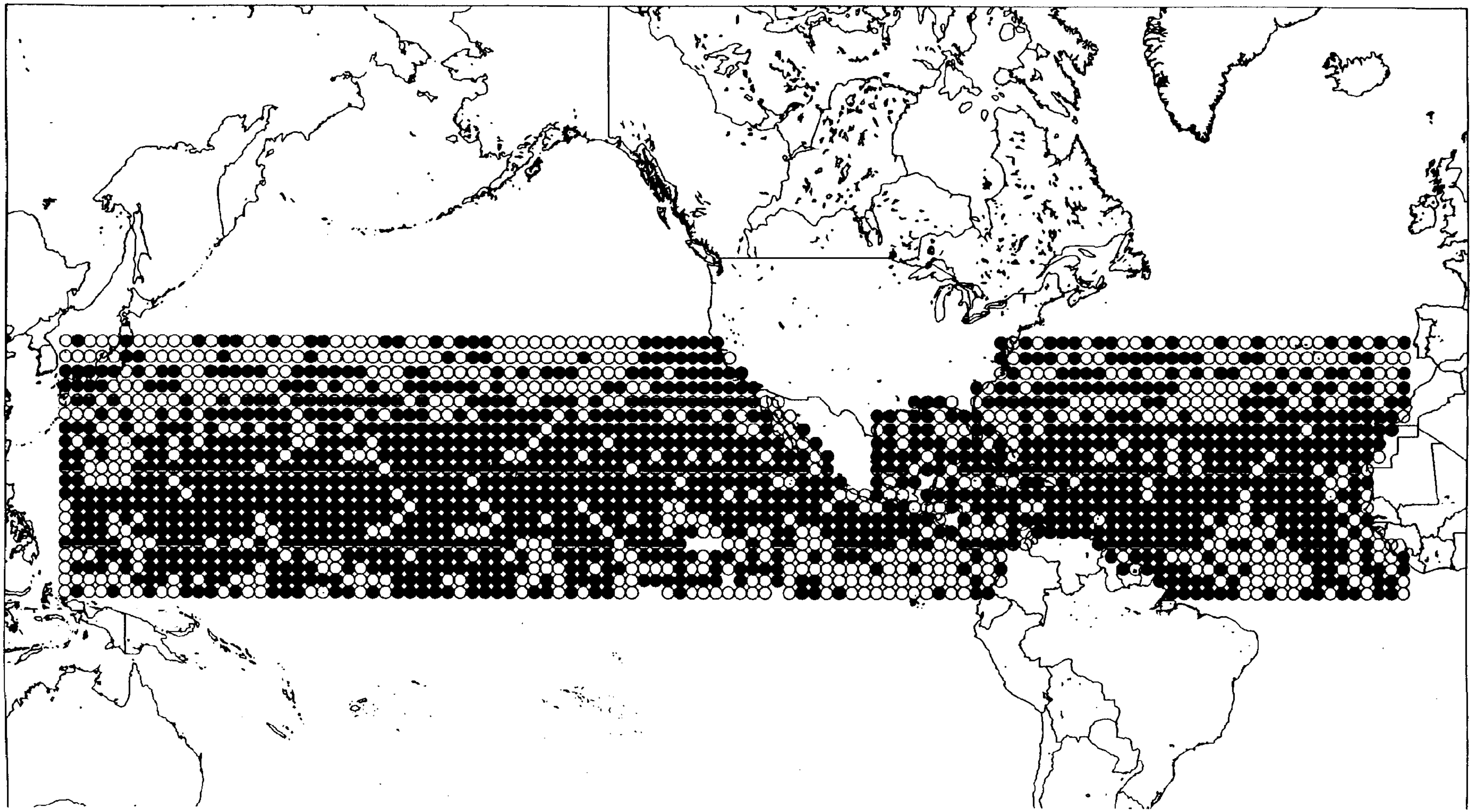

Figure 21b. Wind Direction Anomaly for the Period 1935-1944 Computed from COADS (Shaded Circles Indicate Backing, Open Circles Indicate Veering).

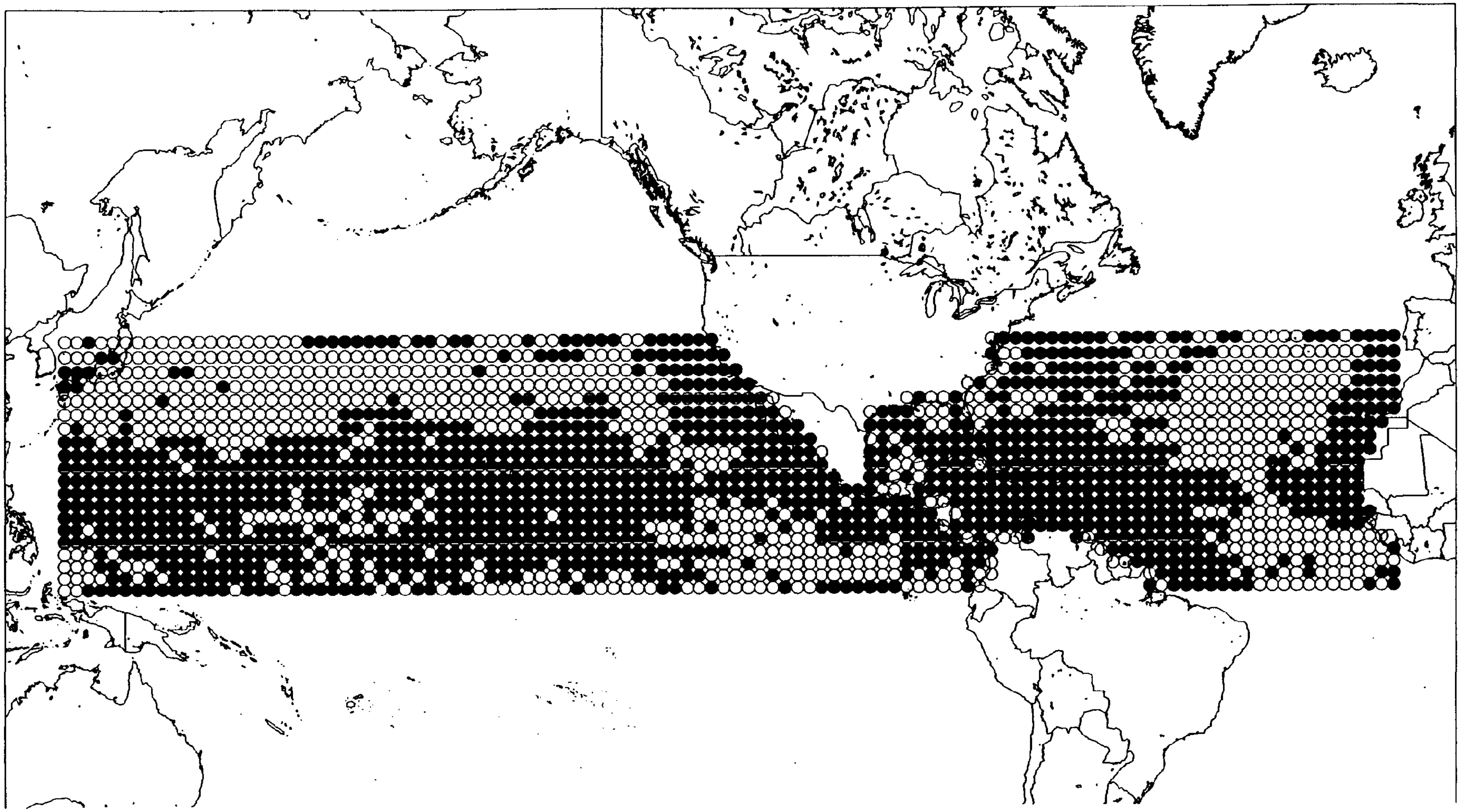

Figure 22a. Wind Speed Anomaly for the Period 1970-1979 Computed from COADS (Shaded Circles Indicate Larger, Open Circles Indicate Smaller).

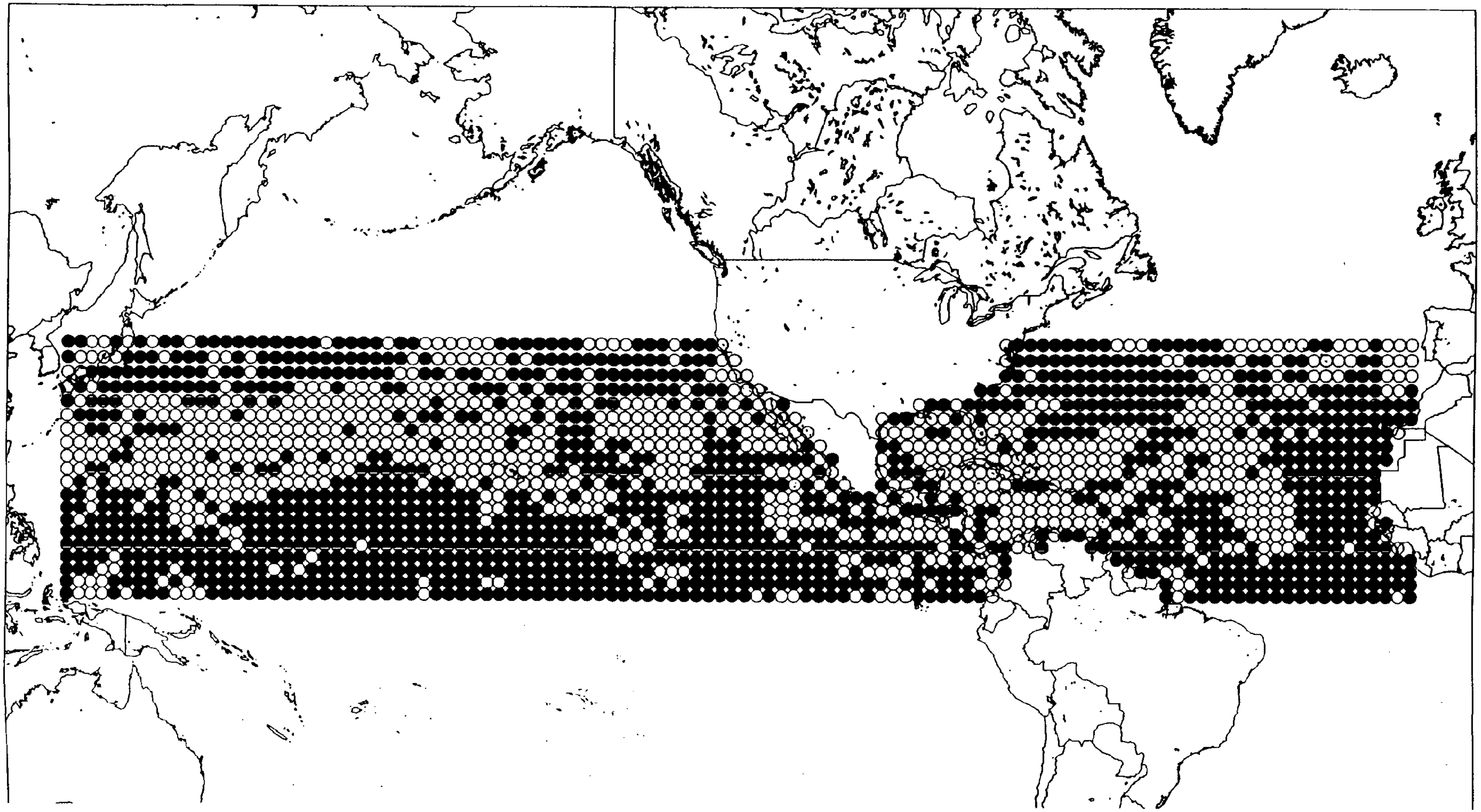

Figure 22b. Wind Direction Anomaly for the Period 1970-1979 Computed from COADS (Shaded Circles Indicate Backing, Open Circles Indicate Veering).

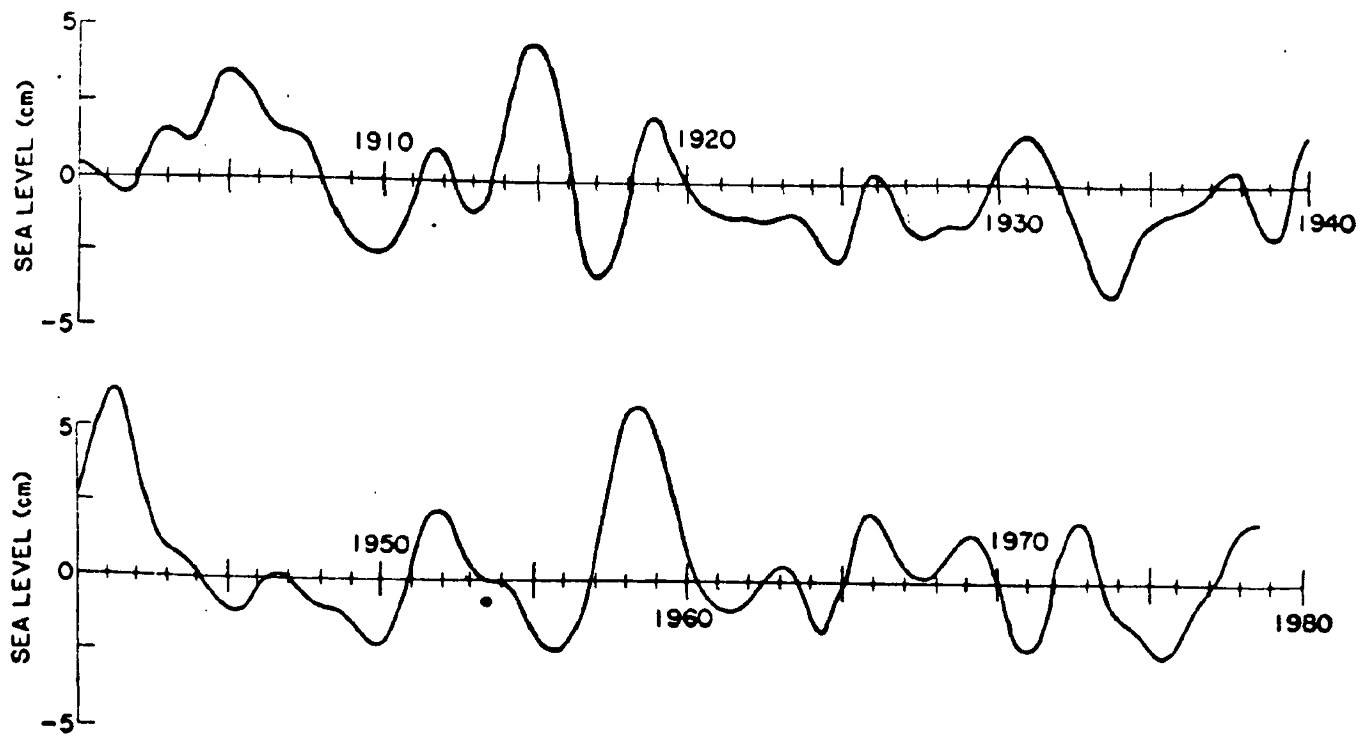

Figure 23. Monthly Average Sea Level Observed on the Coast South of San Francisco During the Period 1900-1979 (Chelton et al., 1982).

3.2 Differences in Ocean-Area Atmospheric Pressure for Selected Periods

The Hadley Circulation produces changes of air mass convergence in the vicinity of the Atlantic and Pacific areas subtropical anticyclones. These changes are monitored by the magnitude of surface air pressures and by latitudinal gradients of pressure variation. Monthly averaged pressures were compared to long-term mean of pressures for each 2° area and these pressure anomalies were averaged over all months and along 2° bands of latitude. Latitude bands in the Pacific area were from 160° W eastward to 130° W and in the Atlantic area 50° W to 20° W. Pressure data were analyzed for the same periods as the wind summaries i.e. 1889-1899, 1935-1944, and 1970-1979 and these anomaly averages are listed in Table 1, Page 53. Since anomalies were computed by subtracting measured pressure from long-term mean, negative anomalies indicate pressure of the latitude band increased during the summary period. Data in the table shows pressure increased over most of the latitude bands in the Pacific area coincidentally with wind veering and increasing in speed in the California coastal area. Similar changes occur in pressure and wind regime with seasonal changes from winter to summer. Conversely, wind backing and reduced wind speed occurred during the period 1935-1944, a period with decreased pressure over the Pacific latitude bands. Latitudinally averaged anomalies in the Atlantic area do not have a distinctive pattern of change from one summary period to another.

In geographic regions of Hadley Circulation, the regions of pressure difference are also regions with cloud-cover differences; areas of low pressure and ascending air-mass are areas with greater cloud amount than areas of high pressure and subsidence. Cloud amounts from the period of climate cooling were compared with cloud amounts from the 1970's period with climate warming to see if changes in Hadley Circulation intensity were causes of observed wind and pressure variations. No distinctive regional differences were discerned but cloud amount in both the Atlantic and Pacific areas was larger in the analysis period from the 1970's compared to the analysis period 1935-44. The cloud differences in our analysis regions appear to be caused by southward extension of cloud associated with meteorological systems in the mid-latitude westerlies. These results do not support the hypothesis that variation of Hadley Circulation intensity was a cause of the observed wind and pressure differences. COADS cloud data were compared to cloud amount derived from satellite data by Godshall (1968) from the period 1962-1973 in the eastern Pacific. Correlation between the cloud amounts was poor with correlation coefficient of 0.53 which suggests the COADS cloud data may be of poor quality.

Averaged surface pressure maps for January months in cold years, with change-to-warmer climate (Figures 24a. and 26a., Pages 54-59), show Pacific subtropical anticyclones were positioned further north and west of normal positions of the anticyclone (Figure A-1.). Cold years anticyclones in the Atlantic were also positioned further north but all anticyclone displacements are small, on the order of a few degrees of latitude. During August cold years periods, there is less difference in the geographic position of the anticyclones (Figures 24b., 26b. and Figure A-2.). Eastern Pacific anticyclones during the 1935-44 period of climate cooling (Figure 25a,b.) are displaced toward the southeast. Changes in the Atlantic area are less than those in the Pacific. Although there are few of the pressure analyses periods for intercomparison, the period differences are evidence for a change in the general atmospheric circulation that includes change in the Aleutians Low and local climate variation identified by others (Namias, 1980 and 1985, Cayan and Peterson, 1989).

Table 1 Pressure Anomaly Averaged Over Two-Degree Latitude Bands From the Periods, 1889-1899, 1935-1944, and 1970-1979 in Pacific (160°-130°W) and Atlantic (50°-20°W) Areas.

	PACIFIC AREA Anomaly (mb)			ATLANTIC AREA Anomaly (mb)		
NORTH (°N) LATITUDES	1889-99	1935-44	1970-79	1889-99	1935-44	1970-79
1	-0.61	-0.17	-0.11	0.48	0.11	0.09
3	-0.74	-0.73	-0.09	0.24	0.12	0.08
5	-0.93	-0.35	-0.18	-0.13	0.12	0.03
7	-1.48	-0.09	-0.21	-0.09	0.09	0.04
9	-0.86	0.01	-0.15	0.02	0.18	0.09
11	0.54	0.09	-0.17	-0.12	-0.04	0.05
13	-0.03	0.31	-0.21	0.10	0.08	0.07
15	-0.59	0.41	-0.22	0.18	-0.04	0.05
17	0.75	0.20	-0.22	0.12	0.10	-0.01
19	0.81	0.01	-0.22	0.01	0.07	-0.04
21	0.14	0.34	-0.24	0.25	0.01	-0.04
23	0.00	0.39	-0.30	0.39	0.00	-0.02
25	-0.12	0.44	-0.23	0.55	-0.17	0.01
27	-0.66	0.37	-0.13	0.69	0.11	-0.02
29	-0.43	0.55	-0.20	0.25	0.21	-0.09
31	-1.76	0.71	-0.36	0.91	0.39	-0.03
33	-1.41	0.95	-0.35	0.84	0.25	-0.09
35	-1.72	0.72	-0.28	1.86	0.51	-0.06
37	-1.49	0.92	-0.52	3.01	0.34	-0.12
39	0.00	0.99	-0.71	-0.11	0.76	-0.29

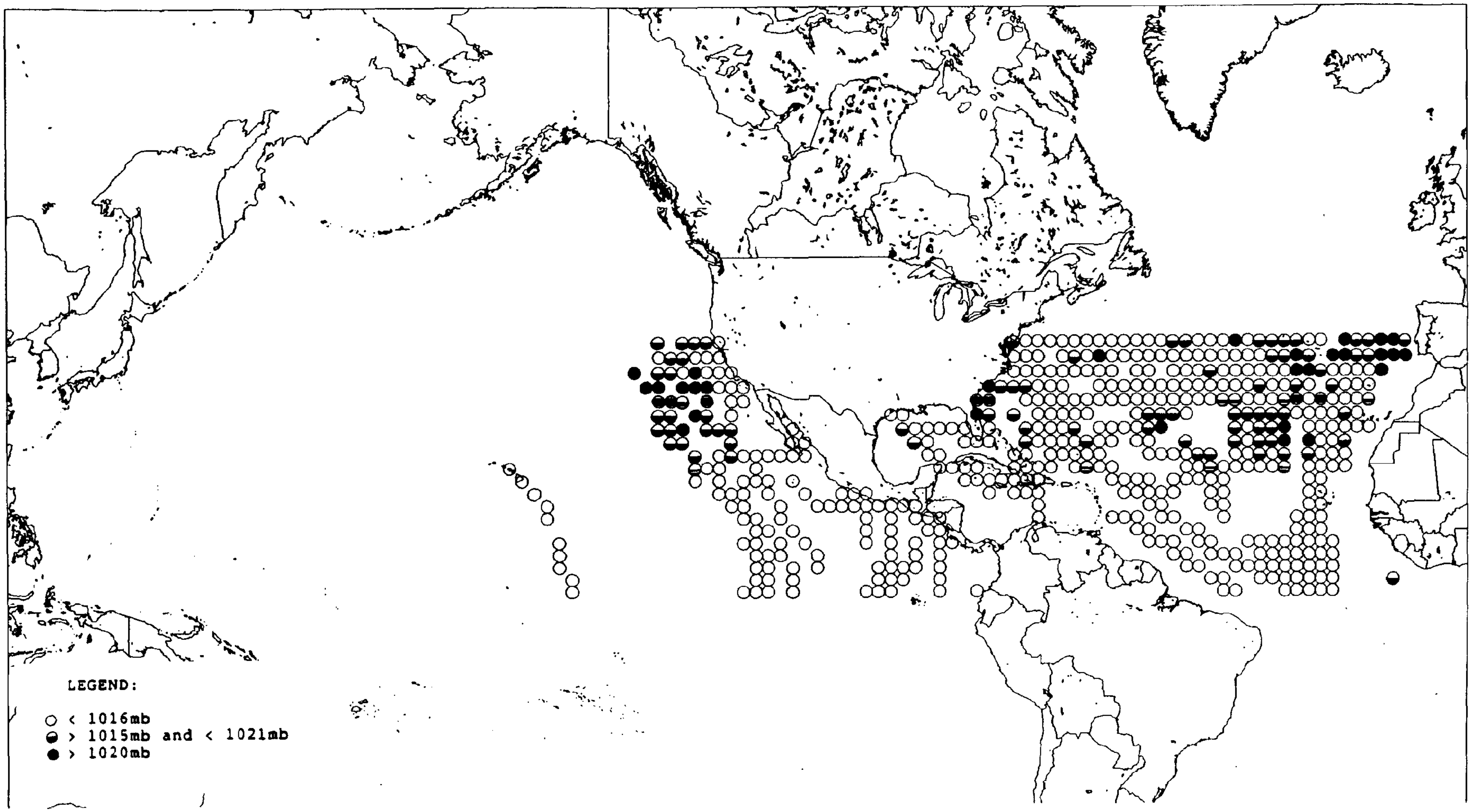

Figure 24a. January Average Atmospheric Surface Pressure for the Period 1889-1899 Computed from COADS.

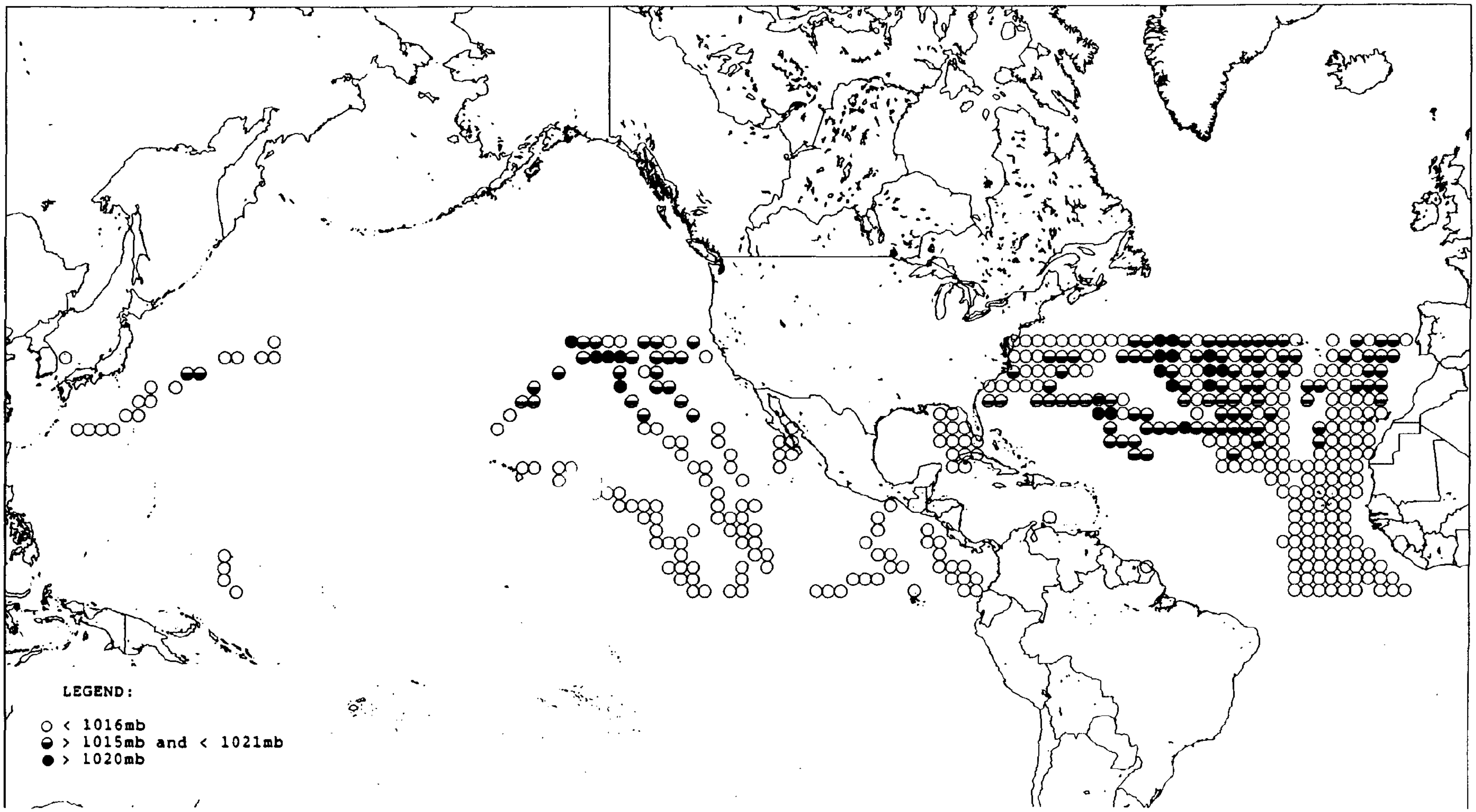

Figure 24b. August Average Atmospheric Surface Pressure for the Period 1889-1899 Computed from COADS.

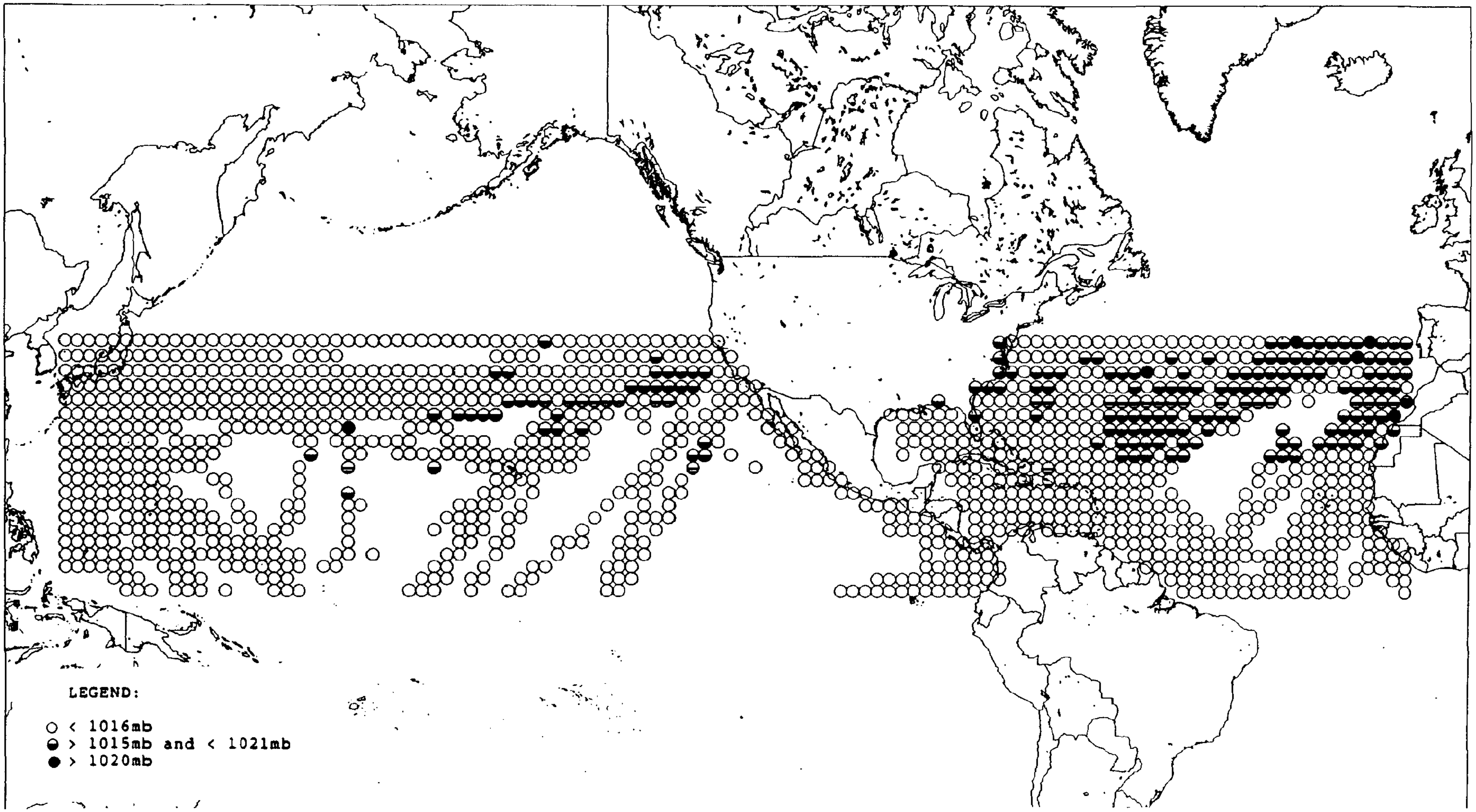

Figure 25a. January Average Atmospheric Surface Pressure for the Period 1935-1944 Computed from COADS.

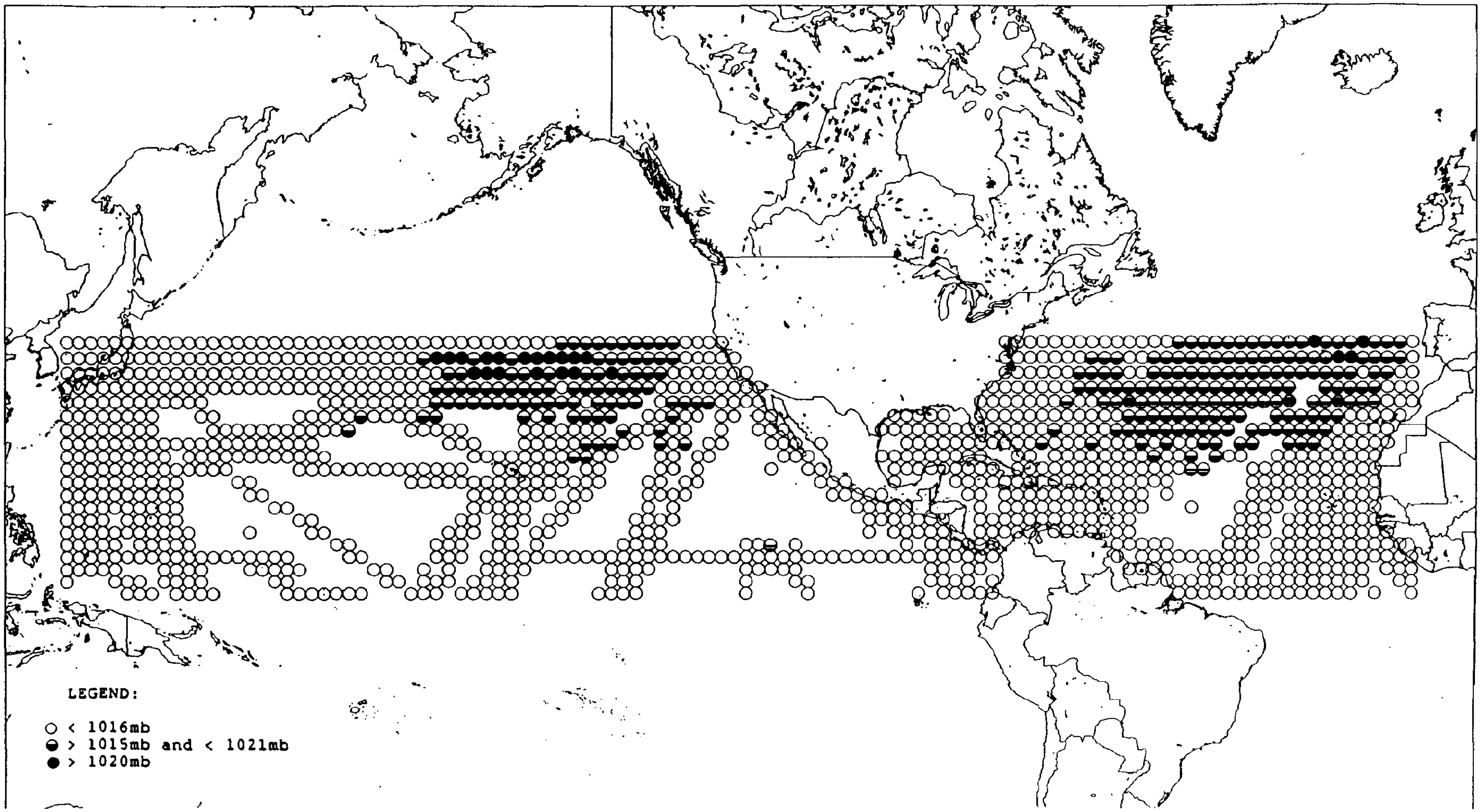

Figure 25b. August Average Atmospheric Surface Pressure for the Period 1935-1944 Computed from COADS.

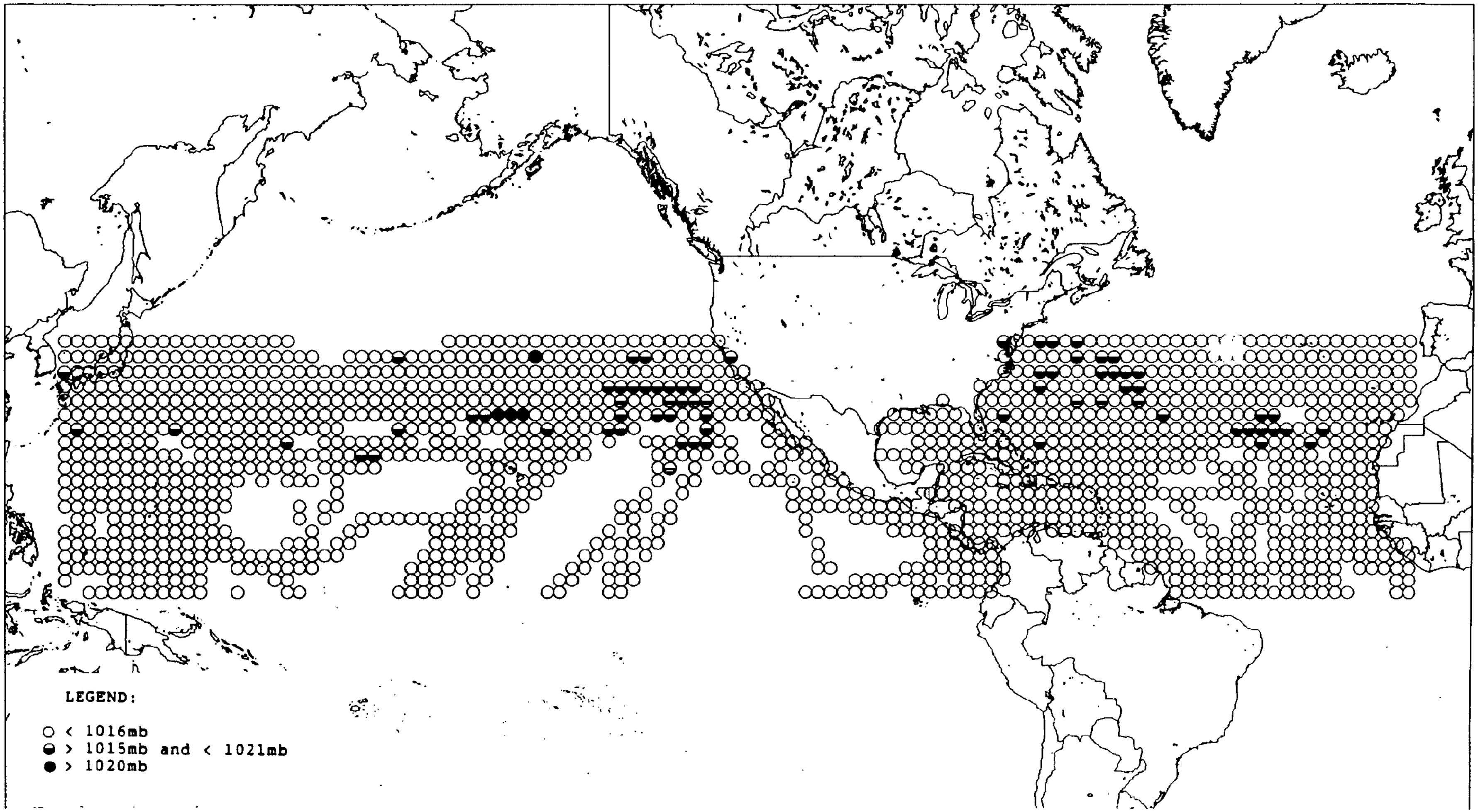

Figure 26a. January Average Atmospheric Surface Pressure for the Period 1970-1979 Computed from COADS.

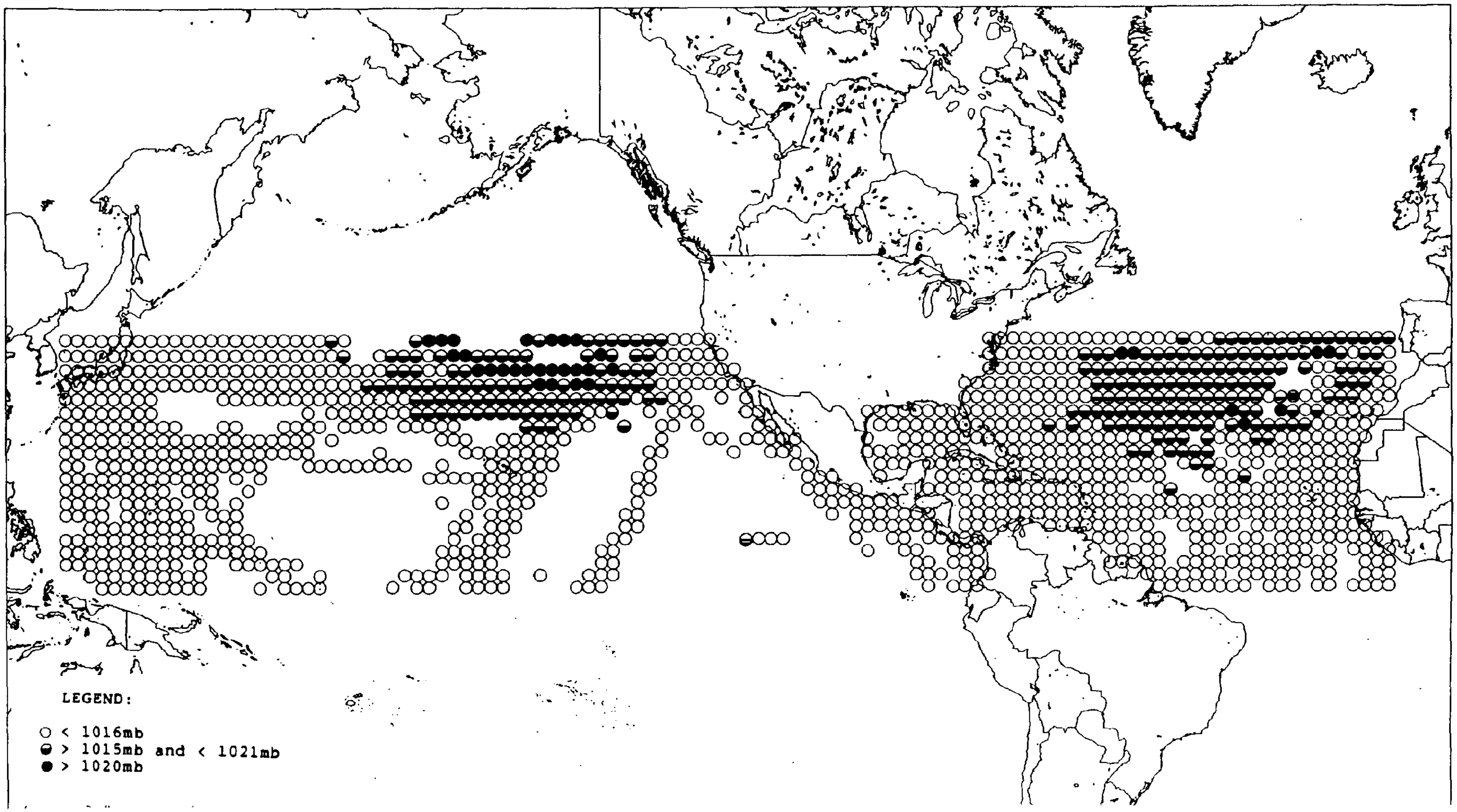

Figure 26b. August Average Atmospheric Surface Pressure for the Period 1970-1979 Computed from COADS.

4. CONCLUSIONS

A basis for assessment of environmental impact in coastal waters is the expected change in the parameters sea-level, runoff and wind effects as a consequence of Global Climate Change. Changes in these selected parameters serve as analogues of change that may occur within the regions for analysis. The analogue approach for analysis of possible climate change effects could be usefully applied to coastal regions not included in this study.

Mid-Atlantic Bight:

Coastal bays of the Mid-Atlantic Bight are expected to be most affected by river runoff changes and water level change. The seaward salinity gradient, the near-shore stratification, and dynamic circulation of the Bight are also dependent on the amount of fresh water flowing onto the coast. The effect of wind forces on the marine circulation is variable over the Bight because of differences in coastal geography relative to prevailing wind. Southerly wind components in summer promote upwelling along the coast and resultant wind stress opposes the dynamic water mass near-shore circulation. These effects retard southward flow of chemical enriched waters of the New York area and promote circulation of oxygen-rich "cold pool" waters shoreward. A GCM simulated warmer-climate-predicted veering and southward turning of surface seasonal winds in winter is supported by the decade wind analyses of COADS for the area. The COADS wind veering and strengthening during periods of transition to warmer climate indicates lengthening of the summer-seasonal circulation period is possible. The effect of this wind forced circulation during cold seasons will be warmer coastal waters that are more saline.

The veered and more southerly wind regimes over southern coastal areas may advect larger amounts of moisture into the U.S. interior that could lead to larger amounts of precipitation and land runoff. However changes in evapotranspiration could have important influences. Gauged flow rate of the Potomac River (Figure 6.) indicates that enhanced river flow rate did occur during the decade of the COADS wind analyses in the 1970's and possibly during the 1890's (both periods of transition from "cold" to "warmer" climate).

Steric effects (water density changes) are predicted to cause continued rise in sea level along the east coast. Wind-forced circulation will lead to lowering of water level but varied geography of the Bight will cause considerable local differences in this effect.

Gulf of Mexico:

The summer, seasonal shelf circulation of the northwestern Gulf of Mexico is driven by southerly wind. Wind changes that extend the season of these winds will promote a longer annual period for existence of the anticyclonic gyre on the shelf. However, it is unclear that an extension of the Bermuda High predicted for a period in transition toward a warmer climate will promote prevailing southerly wind regimes of the western Gulf. In the past, large areas near-west of the Mississippi Delta were impacted by anoxic bottom water events. These conditions occurred with wind-forced spreading of low saline surface-layer water mass that increased the coastal area stratification. Northeasterly winds for these events came from an apparent extension of the Bermuda High/belt-of- subtropical- anticyclones over the southern states.

Given the extent of the Mississippi river watershed, which occupies a large portion of the United States, one might expect to find trends in the river discharge attributable to changes in mid-continental precipitation. However, the records of runoff rate of the Mississippi/Atchafalaya Rivers for this study do not substantiate an association of runoff rate change with transitions from "cool" to "warm" periods.

Sea level rise is expected to continue in the northwestern Gulf area because of land subsidence. Loss of coastal wet lands and barrier islands is expected to continue and result in continued change of coastal bays and salt marsh environment (Edward Klima, National Marine Fisheries Service, personal communication).

Southern California:

In southern California coastal area, winter wind veering may have some influence on the Davidson Current but, of greater possible significance is northerly wind speed increases that will increase upwelling along the coast. From past records, increased upwelling has produced cooler coastal water temperatures and increased coastal salinity levels. Increased northerly wind will cause increases in the California Current and advection of northern California coastal water may have some effect on water quality but this is not assessed in this report.

The COADS wind analysis of the decade of the 1970's was interpreted as a decade with characteristics that are associated with trends toward a warmer climate. A longer period, 1946-88 (Bakun ob. cite) was also identified as a period with increased northerly wind and coastal upwelling even though the longer period included part of a period of Northern Hemispheric cooling.

The negative correlation of river runoff in southern California coastal areas with atmospheric pressure reported by Cayan and Peterson (ob. cite) is expected from the analyses of COADS pressure data. From COADS analyses lower pressures were found to be characteristic of the decade from 1935 and runoff rate of the Arroyo Saco River is much greater during this same period (Figure 10., Page 26). Namias (1980) found the dry 1975-76 period to be associated with lower pressures in the north central Pacific with higher pressures on the southern California coast. The flow rate in the Arroyo Seco is very low in this period (Figure 10., Page 26). COADS analysis of pressure found the coastal area pressures to be higher than the long-term mean in the periods in transition toward warmer climate. Therefore, precipitation and runoff from rivers in southern California are expected to decrease in the future as climatic warming continues. Although runoff carries plant nutrients into coastal water masses, decreased runoff may not be important for coastal productivity because the expected increase of northerly wind will promote advection of nutrients into the surface layers from upwelling.

Dynamic causes of sea-level change are important factors for change along the coast. Coriolis acceleration of coastal water masses causes lowered coastal sea level; seasonal change of southward directed wind stress produces an annual sea level change of about 20cm. This amount varies along the coast because of local geography and bottom topography of the shelf. Changes in sea level are expected to have little impact along the coast because of the general steepness of coastal terrain.

The Next Steps:

Changes in the atmospheric coastal circulation of the past substantiate prediction of circulation change by the GFDL General Climatic Model. The atmospheric circulation is used to infer a coastal-marine circulation along the open coast that is expected in an environment with atmosphere doubled carbon dioxide concentration. This coastal circulation and other parameters of future climate are expected to cause environmental change in coastal bights and bays that are different from change on the open coast. Large estuarine areas, such as Chesapeake Bay, are expected to have large hydrographic change caused by coastal circulation and sea level and also precipitation/river runoff. These areas are important for assessment of coastal responses because the estuaries are, in many aspects, a focus of concern regarding coastal resource exploitation. Operation of the numerical models of runoff and circulation for the Cheasapeake Bay from scenarios of changes in climate will permit evaluation of potential impact in the context of changes related to larger scale processes.

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APPENDIX A

MONTHLY MEANS OF ATMOSPHERIC SURFACE PRESSURE

MONTHLY MEANS OF ATMOSPHERIC SURFACE PRESSURE

INTRODUCTION:

The months of August and January were chosen to represent the summer and winter seasons of the northern hemisphere for the longitudes of the United States because the mean position of the Intertropical Convergence (ITC) zone (Godshall, 1968) is furthest north in August and at the southern most position in January. COADS (NOAA, 1985) 2° square average surface data in the period from 1854 to 1979 were averaged to produce the January surface analysis (Figure A-1.) and August analysis (Figure A-2.).

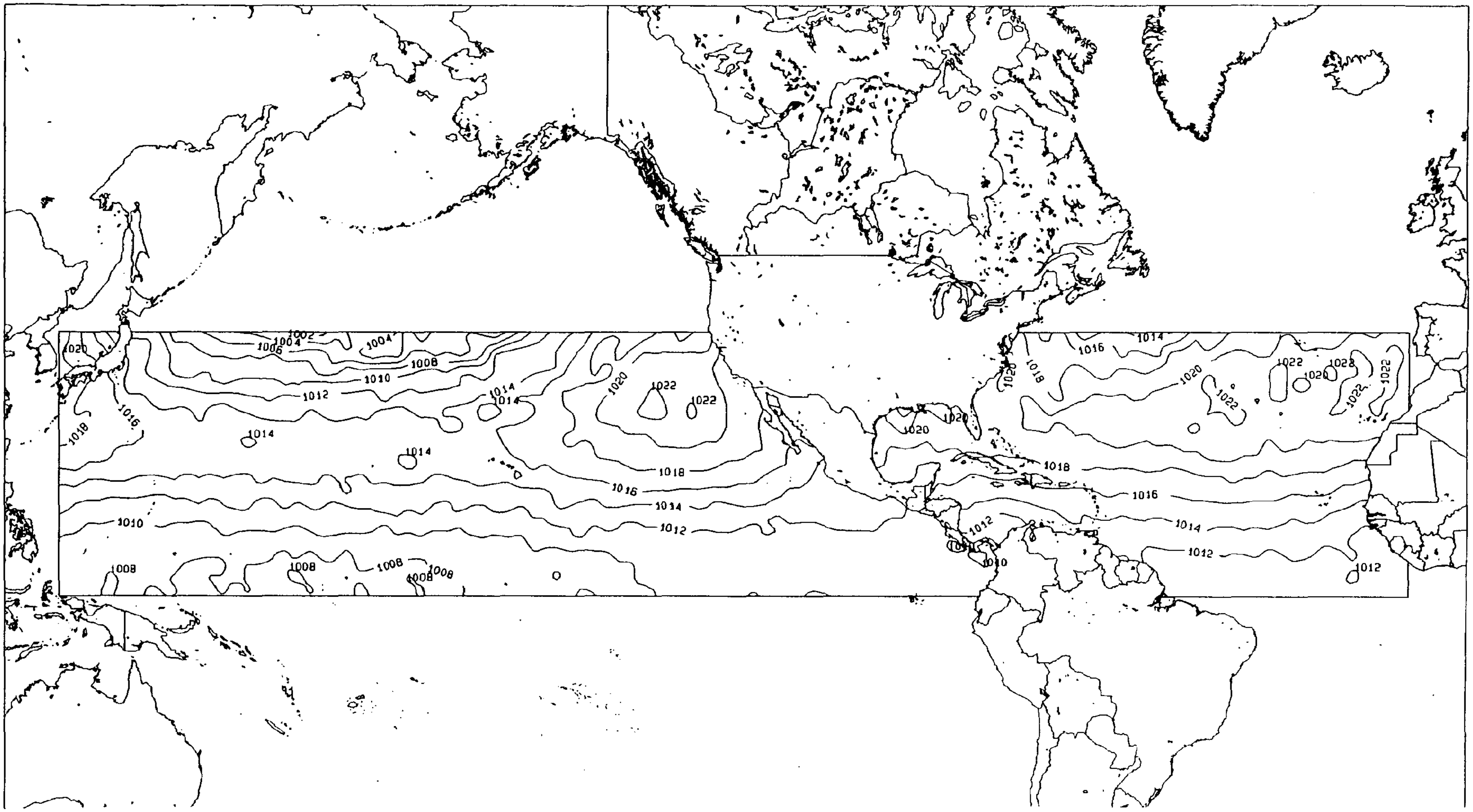

Figure A-1. January Mean Atmospheric Surface Air pressure.

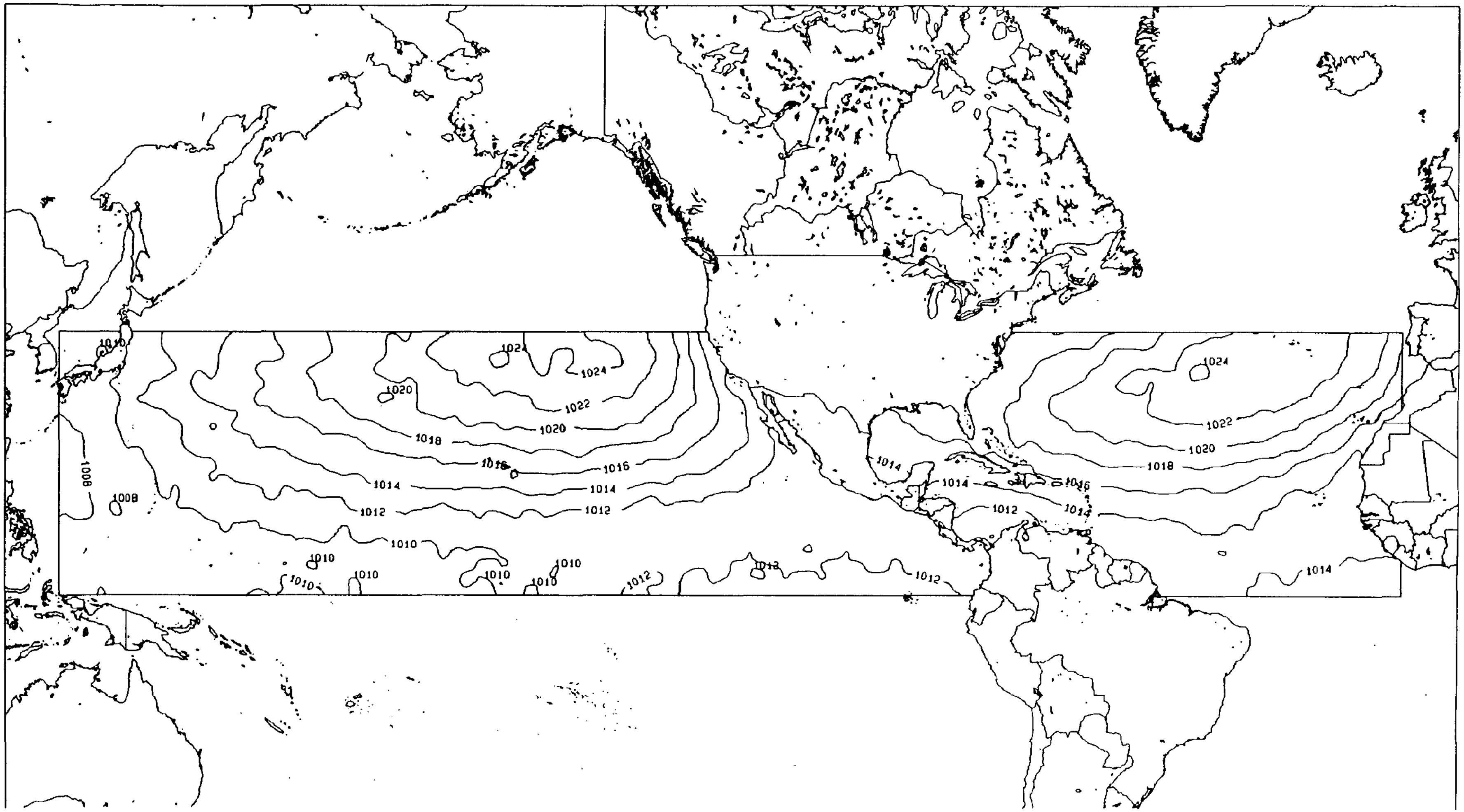

Figure A-2. August Mean Atmospheric Surface Air Pressure.

APPENDIX B

VECTOR ANALYSIS OF WINDS

APPENDIX B

WIND VECTOR ANALYSIS

INTRODUCTION:

Wind observations are usually reported as vector quantities with magnitude and direction. This analysis procedure uses sets of pairs of wind observations. The procedure seeks a wind speed factor nu (ν) and a wind direction factor phi (ρ) that will adjust a set of the paired wind observations so there will be a minimum sum of squared vector differences for the set. In this climate variation study, the sets consist of long-period monthly mean wind vectors from each 2° geographic area of the COADS summary paired with the average monthly winds of the square area. The nu and phi factors are the vector characteristic differences of the 2° square area yearly winds from the long-term means.

Vector Differences:

The wind vectors (R_1) from one set, $R_1 = \rho_1 \exp(i\,\theta_1)$ are compared to a second set of vectors, $R_2 = \nu\,\rho_2 \exp(i\,(\theta_2 + \phi))$. With (j) wind vectors in each of the sets, ρ_{1j} and ρ_{2j} are the wind speeds, θ_{1j} and θ_{2j} are wind directions, and (i) is the imaginary number exponent of the complex numbers representing the wind vectors. With E representing the amount of squared inequality between R_1 and R_2 pairs in a group of N observations,

$$\sum_{j=1}^{N} \rho_{1j} \exp(i\,\theta_{1j}) - \nu\rho_{2j} \exp(i\,(\theta_{2j} + \phi))\ ^2 = \sum_{j=1}^{N} E_j$$

After expanding the squared difference, differentiating E sum with respect to nu and then with respect to phi, and setting the differentials equal to zero, the differentials may be solved algebraically to produce equations for nu and phi. These nu and phi are the factors to make the squared vector differences a minimum.

$$\text{NU} = \frac{\sum_{j=1}^{N} (\rho_{1j}\,\rho_{2j})\,\text{COS}(\theta_{1j} - \theta_{2j} - \phi)}{\sum_{j=1}^{N} (\rho_{2j})^2}$$

$$\text{PHI} = \text{ARC TAN} \frac{\sum_{j=1}^{N} \text{SIN}\,(\theta_{1j} - \theta_{2j})}{\sum_{j=1}^{N} \text{COS}\,(\theta_{1j} - \theta_{2j})}$$

APPENDIX C

MONTHLY WIND FIELDS OF LOW LATITUDE REGIONS OF THE ATLANTIC AND PACIFIC OCEANS

MONTHLY WIND FIELDS OF LOW LATITUDE REGIONS OF THE ATLANTIC AND PACIFIC OCEANS

INTRODUCTION:

Monthly vector-averaged wind fields were computed from COADS (NOAA, 1985) for the area 130° E eastward to 10° W longitude, 0° to 40° N latitude. Based on climatology of the Intertropical Convergence (ITC) zone (Godshall, 1968), August was selected to represent the summer season and January was selected to represent winter. Monthly vector-mean wind was computed from the COADS 2° square averaged wind components and analyzed to illustrate the broad-scale surface wind regimes. During January (Figure C-1.), the westerlies are found over the northern part of the study region, the subtropical anticyclones and trade winds are relatively weak, and the ITC is at it's southern most position in the Atlantic and Pacific oceans. During August (Figure C-2.), the westerlies barely get into the study area, the trade winds are relatively strong, and the ITC is at the northern most position.

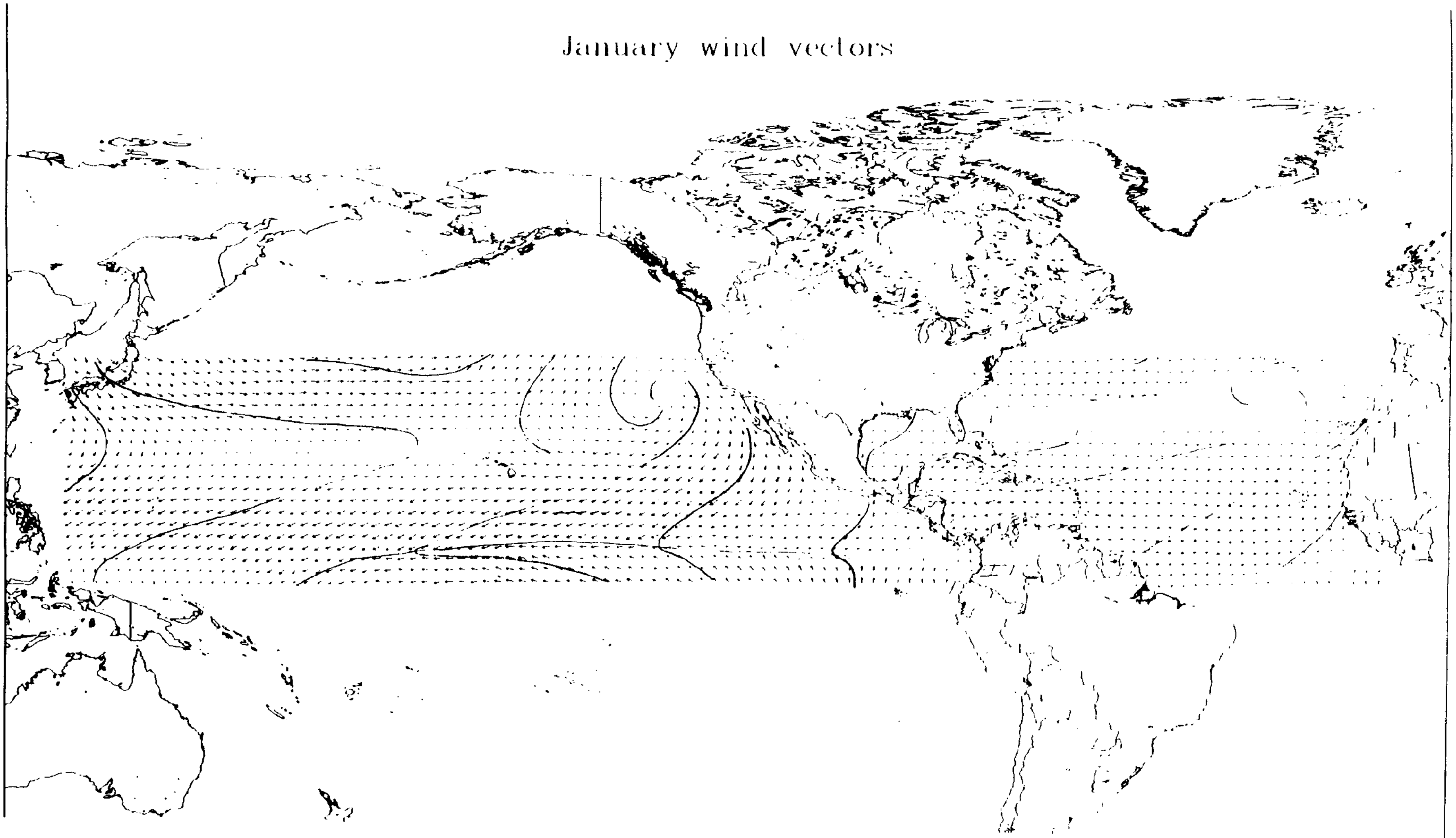

Figure C-1. January Vector Mean Surface Winds.

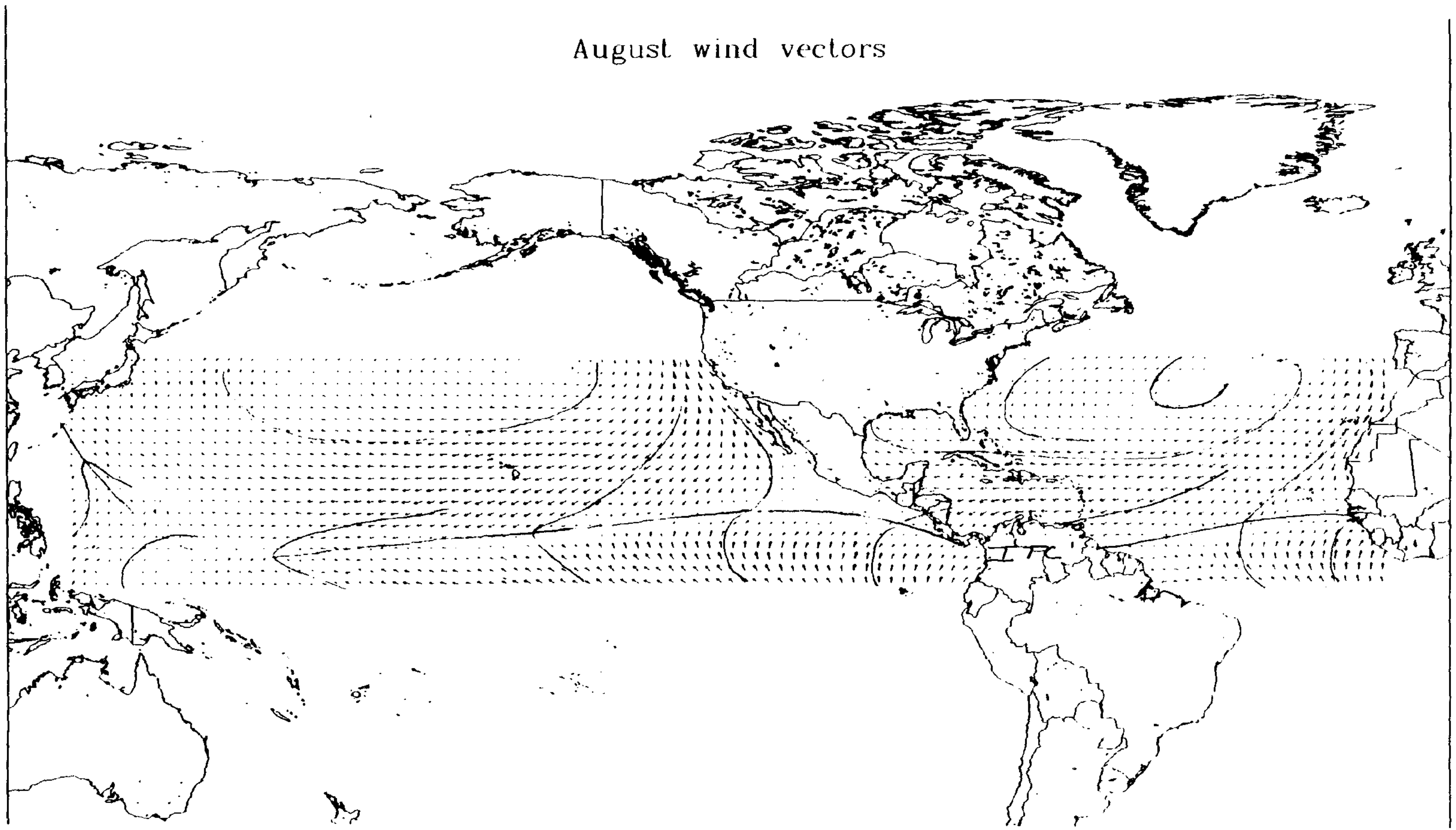

Figure C-2. August Vector Mean Surface Winds.